# Electrical Engineering

April
1936

North Eastern District Meeting—New Haven, Conn.—May 6–8, 1936

Published Monthly by the
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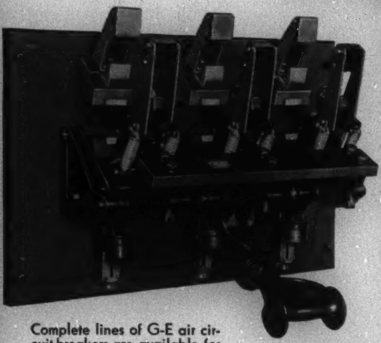
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## Front Cover

**The Green in New Haven, Conn., where the Institute's forthcoming North Eastern District meeting will be held. Since 1640, only 2 years after New Haven was settled, the Green has been the heart of the city. Behind Trinity Church (third church on the left) is the Hotel Taft, while in the right background is the famous Harkness Memorial Tower, overlooking Branford College, Yale University.**

Photo courtesy Coleman Brothers Co.

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# In This Issue—

ANY attempt to delete from the engineering curriculum any subjects that are necessary for successful engineering in order to make room for more or less unrelated subjects is a step in the wrong direction. So speaks a well known engineer who has had an opportunity to observe at close range many engineers in action, in discussing the situation in which the young engineer may expect to find himself under currently changing conditions (*pages 329–34*).

TORQUE in the rotating disk of an induction watt-hour meter usually is computed on the basis that the eddy currents in the disk flow around the inducing pole in a series of concentric rings; this assumption, however, is not valid when the pole is located eccentrically with respect to the axis of the disk. A torque formula based upon the actual current distribution is given in a paper in this issue (*pages 354–8*).

SWITCHING surges may be of sufficient magnitude under certain conditions to damage the turn insulation on the windings of high voltage rotating machines. This problem is one of growing importance because of the desire for full line voltage starting of 11 to 13.8 kv motors, and because of the desire to bring all such machines on the line with the minimum of switching (*pages 376–84*).

THE Institute's 1936 summer convention, to be held at Pasadena, Calif., June 22–26, offers attractive possibilities to those contemplating combining attendance at the convention with vacation trips. A special train leaving from Chicago is contemplated, and a tentative itinerary with stopovers at many points of interest along the route has been suggested (*pages 418–19; 328*).

INDUCTION motors suffer a reduction of maximum torque, output, and efficiency when operating under unbalanced conditions, whether this unbalance is in the applied voltage or in the external circuits of the motor, such as starting and control circuits. General equations for induction motors under such conditions are given in this issue (*pages 386–93*).

ANALYSIS of steady state or transient conditions in electric power systems generally can be simplified by the use of equivalent circuits. Equivalent circuits representing 2 coupled circuits under various conditions are developed in a paper in this issue, and their application to power system circuits is discussed (*pages 366–71*).

FLASHOVER characteristics of transmission lines may be estimated with reasonable accuracy by means of curves, data, and procedure presented in a paper in this issue. Such information is valuable in predetermining the improvements that can be realized by relatively inexpensive changes in existing lines (*pages 342–54*).

DIESEL-ELECTRIC equipment has undergone considerable development and improvement in connection with its increasing use in high-speed light-weight streamline trains. Further progress may be expected in the future; lighter weight per engine horsepower, equipment of greater horsepower, and greater efficiency are predicted (*pages 335–41*).

MANY people think that engineering and scientific developments have advanced beyond our social absorption ability. The noted head of a large research organization says that engineering is *a lap* behind (*pages 324–8*).

IN an effort to eliminate the uncertainty arising from the assumed constants involved in the calculation of zero sequence impedances of underground power transmission cables, impedance measurements were made on the 27 kv system of a large eastern metropolitan power company (*pages 359–65*).

OVERREFINED or readily oxidizable oils in transformers will maintain automatically an inert gas above the oil. It is reported that transformers equipped for restricted breathing can be operated with overrefined oils for long periods without servicing so far as the oil is concerned (*pages 371–5*).

SINCE April 1929, the principal activities of the Institute's New York Section have been carried on by groups representing the main fields of interest of the members. These group activities have been highly successful and are proving to be increasingly popular (*pages 421–2*).

NORTH EASTERN District meeting of the A.I.E.E. to be held in New Haven, Conn., May 6–8, 1936, is announced in this issue, including the technical program and other details. The meeting will include interesting inspection trips and social functions (*pages 416–17*).

ELECTRIC shock experiments to determine heart reaction to currents of different frequencies, using both interrupted direct current and alternating current, have led to significant results under these conditions (*pages 384–6*).

APPLICATIONS for membership in the A.I.E.E. received at Institute headquarters between May 1935 and March 1936 are 19.1 per cent higher than those received during the same months a year earlier (*pages 420*).

LETTERS to the Editor columns of ELECTRICAL ENGINEERING continue to attract contributions from readers on a variety of subjects (*pages 424–5*).

ONE of the 6 major inventions or discoveries of James Watt was the knowledge of the expansive force of steam (*page 358*).

DISCUSSIONS in this issue include the first group published on papers presented at the Institute's 1936 winter convention (*pages 393–415*)

# Professional Recognition

## —A Message From the President

CENTURIES ago the responsibility of the individual citizen was a highly prized privilege that set him apart from barbarians and slaves, as it has ever since. Such privileges have been difficult to win and just as difficult to maintain. Indifference, corruption, widespread disaster, and dissatisfaction have led to gradual or revolutionary usurpation of freedom and the popular will. Also, the complications of changing conditions have been further increased by the rise in technology.

In modern times we have come to recognize and accord special privileges to practitioners in a great number of fields of endeavor.

During recent years the unsatisfactory status of the engineer in this regard has served to awaken in him a consciousness that he, himself, is in large part responsible for the conditions confronting him, and that no improvement can be attained without earnest effort on his part to place the profession in its proper rôle as a vital unit in the sphere of public activities. In the past he has remained almost entirely aloof from all interests not concerning him technically, with the result that when the nation was faced with economic collapse, he was among the first to suffer the hardships of privation and was almost entirely overlooked in the widespread emergency efforts to plan for general recovery.

Only comparatively recently were definite steps taken to bring about official and general recognition of the engineering profession. The clamor for professional recognition, which had been increasing in intensity over a number of years, culminated in 1932 with the formation of the Engineers' Council for Professional Development. This body was formed as a central agency to advance the status of the engineer, and at present its efforts are being directed along 4 lines: (1) a study of processes and methods to guide men into or out of engineering colleges, (2) a study of the possibilities for cooperation between the practicing profession and the engineering colleges, (3) a study of methods to aid in post-collegiate training, and (4) a study of possibilities for correlating methods for the formal recognition of engineers as professional men.

The establishment of specific means for recognizing the curricula of engineering schools and the granting of corporate membership in engineering societies are 2 procedures which will become more universally recognized and accepted as harmonizing with the attainment of professional status, but much remains to be studied and evaluated before full attainment can be expected.

The registration of engineers, it appears, is an important element in the unified approach toward the establishment of adequate means for recognizing the engineer as a professional man.

Engineering registration of some form is with us today. There is also a well-defined movement under way to increase the number of laws and restrictions governing the practice of engineering. The problem, therefore, should be considered with respect to the long-time effect on the profession, as well as its immediate effect on the engineer.

From a long range viewpoint, it is important to determine whether licensing of the best form will benefit the electrical engineer. If the American Institute of Electrical Engineers does nothing for or against licensing, laws may be passed or modified to the disadvantage of electrical engineers as individuals and of the Institute. Undoubtedly, modifications proposed will favor the licensed engineer and react to the disadvantage of those who are not licensed.

The work of the Engineers' Council for Professional Development obviously may not be expected to be consummated in a short time, but progressive steps are and should be attainable through careful study of the problem and education of those most vitally interested, namely, the members of the profession itself.

The situation must be faced squarely. It is the profound duty of all engineers to affiliate themselves with the work of the Council which is dedicated to their welfare and pledged to the mutual benefit and protection of the interests of the entire engineering profession. Your individual support is essential in bringing about a generally accepted concept of what is termed the recognition of an engineer, and you cannot afford to deny it to yourself or the profession.

The long and honorable record of any institution, and especially of the institutions whose achievements are the result of the successful cooperation of a large number of individuals, is not grounds for admiration and respect merely, but for serious consideration in determining a course of action which affects its own future and that of those for whom it is most deeply concerned.

# Research and Social Progress

**Being essentially the full text of the address delivered in Chicago, February 25, 1936, in response to the receipt of the Washington Award "in recognition of devoted, unselfish, and pre-eminent service in advancing human progress," this article is published at the instance of the A.I.E.E. committee on education.**

By
CHARLES F. KETTERING
FELLOW A.I.E.E.
General Motors Corp.,
Dayton, Ohio

SOMETIMES we need to define words in order to get at the meaning—I mean more than the superficial meaning. We sometimes mistake what the word "research" means. There is a great difference between the meaning of the word "planning" and the meaning of the word "research." To plan beyond our ability to do may or may not be a right thing, but if the planning is of the right order of thought, while the desired result may not be obtainable at the present time, a constructive research upon that subject may, and very likely will, bring the result.

Most people think of scientific research as being something to reduce the man hours required to perform any given task. I do not know how that has gotten into our thinking. All the time we hear the subject of technological development talked about as something that is negative. Only in the last phases of technological development does this question of man-hours economics become an important factor. We have forgotten entirely the other and many times more important factor—the development of new jobs and new industries.

You know, engineers have been blamed very largely for the present depression. . . .However, I do not feel that that is the case. . . .We are told by reliable statistics that there is something like 40 billions of dollars idle in American banks. We are also told that there is something between 5 and 15 millions of people out of employment. The number . . .is entirely dependent upon which party you belong to. Nevertheless, there is an unemployment problem and there is a financial unemployment problem. Now, the reason that we have that is because both of those things are ends of the same stick. If we had new products, new projects, new reconstructive type of industry, we would have our money employed and we would also have our people employed.

A great many people think engineering and scientific development has gotten ahead of our social absorption ability. I wish that we would look at it in a different way. . . .I think that maybe the reason that we think engineering is ahead, is because it is *a lap* behind.

In the development of any new industry, it doesn't come full blown. It doesn't come as a completed entity. In fact, I doubt whether anybody ever was conscious of creating an industry at the time it was started. Certainly Oersted didn't know he was creating an industry when he held an electric wire over a compass needle and found it was deflecting. He had searched for that for a long while. Michael Faraday came a little bit farther and wound a coil. Our own Joseph Henry, in the United States, was a contemporary in the development of the magnet. But in that simple thing of winding a coil on a bar of iron the fundamental principle of telegraph was developed, and our Morse, taking that as a clew, succeeded in developing the principles. . . of our present telegraph. But the development of these elementary principles into the enormous communication system that we have today. . .represents millions of dollars of expended money, heartaches, hundreds of thousands of hours, disappointments, discouragements, and everything else. Between the elementary principle and the finished commercial product comes the great work field in which industry has made its progress.

Alexander Graham Bell. . . . .in trying to facilitate the methods of sending messages discovered the principle of the telephone, and out of that came another new industry that employed thousands of people, and put much money to work. . . . .nobody thinking at the time. . . . .that what Bell had discovered represented the basic principle of a new industry. Out of that and other important developments came the principles of radio and other things unthought of and undreamed of only a few years ago.

So, today, as we discuss engineering relationships of science and industry and social development, we hardly recognize that there was a time that we did not have some of these things. We hardly recognize that today you can send a message around the world in a seventh of a second, if you have anything to send. We hardly recognize and do not appreciate that while we can send a message to the farthest point of the earth in a fourteenth of a second, it may take years before it gets from the outside of a man's head to the inside.

Discussing this with a scientist I asked him how he accounted for it. He said the only way he could account for it was by the relative densities of material.

I was talking to a young man one day and he said, "I think there ought to be a halt called on scientific and engineering developments, because we have gone faster than we are socially able to absorb." I happened to be sitting at the desk. I said, "Let's make a phony telephone call. Let's take. . . . .that telephone and tell the operator that you would like to speak to the clerk of one of the great hotels in London. . . . .In a few minutes that bell will ring and you can talk to the man overseas. . . . .Now how much

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did you have to readjust yourself in order to speak across the sea over what the readjustment would have been had you called a department in your own institution?"

It is not the things that we have today that are wearing us from the standpoint of social development. It is the imaginary things we think we are going to have that we don't quite understand.

I asked him if he had any trouble absorbing the improvements that have been made in medicine; whether he felt that he had socially outrun the improved ability to remove an appendix; how much development he had to do socially, mentally, or otherwise to get the benefits of the best surgeons in the world? So, I think it is only foolish for us to say that we are not able to absorb socially the developments that we have. The thing that we need to do is to work out the economics of those things so they can flow infinitely more freely than they do. In other words, we have many things developed today that should have a wider distribution, and I do not know whether it is up to the engineer to work out the economics and the method of distribution of those things or whether that belongs to the so-called economists.

In every industry and in every age we always have wished for things that we didn't have. We have had in engineering, as we all know, the idea of perpetual motion. . . . .We have had the idea of having a machine which, once started, would keep running forever with nothing put into it, and with us taking out any amount of power that we want. The idea of perpetual motion is as old as thinking man, but it is only recently that that particular type of thought has been applied to economics.

A great deal of our fantastic economic thinking is nothing but the same old idea of perpetual motion. If it works, it is wonderful; if it doesn't, then we will have to do as we have been doing: work.

. . . . .We sometimes, I believe, fool ourselves by saying that we know a great deal scientifically. We do know how to operate *some* of the factors to our benefit. We have been able, especially in sanitation and in medicine, to improve human welfare and living conditions tremendously. We have in many other of the mechanical arts been able to do many things which people want. I think the best way to evaluate those things is to try to turn time backward; in other words, let's see what would we do if we didn't have this or that? I happened to be talking to a friend of mine the other day who was making a trip in an automobile from Detroit, Mich., to Miami, Florida. It was the celebration of the 25th anniversary of a similar trip he had made. Twenty-five years ago there wasn't a single mile of paved road between Detroit and Jacksonville, Florida, to say nothing of how few in Miami. All the pavements we had were in the towns, but now, as we know most of the pavements are in the country.

We have forgotten that in that 25 years the enormous development of the motor car as a leader in industry has produced an almost complete change in our method of living. It isn't the automobile from a manufacturing standpoint that is represented by that industry. Some 30-odd years ago I had a canvass made of the number of people employed in the motor car industry. . . . .The best figures I could get were about 1,000 people. The best figures that we have today are that there are about 11,000,000 people directly or indirectly being sustained by that industry. Certainly it isn't in the manufacturing of motor cars that that number of people are employed, but that is not the motor car industry. The motor car *industry* is everything that goes with it. . . . .the highway from the civil engineer. . . . .steel from the mechanical engineer. . . . .[products of] the chemists . . . . .all the things that go into it. A large percentage of our steel is used in motor cars. Enormous percentages of our glass, still larger percentages of rubber, and an extremely large percentage of our petroleum industry is the motor car industry.

No one thought when he was making the old one-lung automobile that he was developing not only a fundamental leader in industry, but also was developing an accessory industry for every one of those that are now existent. You can't tell what an idea . . . . .is going to lead to. You can only make the contribution of the principle; if it serves a purpose, then an industry develops. Industry grows like corn. You plant the seed and you wait until the development comes. If the industry is small it grows in a short time. If it is a great industry it takes a long time. The great developments of both our electric lighting and our telephone industries came in the second 25 years of their existence. And so, with these great industries still incompleted, we haven't any idea what is before us, but. . . . as long as we recognize that we don't know much about them, as long as we recognize that there is human demand for many things of which you and I cannot think, we ought to have faith enough in our ability and in our natural disposition. . . . .to go ahead.

I do not feel that anybody should be discouraged, and never have, because out of all of these experiences it is impossible even for those in industry to project industrial developments a few years ahead. I have been associated with the motor car industry for many years and yet I have never seen even the best forecaster in the world able to tell what was 2 years ahead even in that highly organized field. What can we do that we haven't done? People say, "What are the next great industries?" You can't tell what they are because you don't know when an industry is starting. You can't tell what is going to come because as long as some of the factors are not there, it doesn't develop. The radio, with its principles developed far in advance of our present vacuum tubes, became an industry almost overnight. Another interesting thing is that in the technical study made by the amateurs who sat up all night to try to telegraph across the street were developed the [present radio] technicians. Radio became an operating facility rapidly because of the ready availability of these trained men who had been the amateurs. They were self-educated. Why did they want to study radio? Because they wanted to go into business? No, they hadn't any idea it was a business. It was something they wanted to do. It was an adventure. It was a pioneering effort. What did they expect to get out of it? They hadn't any idea. It was something that looked as if it needed to be done, and they wanted to do it.

Now we have, perhaps, in the last few decades, become too expert in bookkeeping. We begin to think of return on capital, and yet every motive of our life is determined not by return on capital. When you buy a dining room table do you try to figure out what the earning on that is going to be, what per cent you get on your invested capital? When you send your boy or girl to school do you try to figure a net return on that? I sometimes think that if we tried to raise human children on the same basis as that of the highly organized bookkeeping system upon which we are trying to raise industrial children, a baby 9 months old would have to be earning its living.

The engineer must do one great thing: He must teach his financial supporters how to raise industrial children. Remember that a great many of our adventures came as just the natural flux of picking up this thing or that thing and turning it into a useful tool. But as time has gone on, the technicalities of this development work have become greater. Today, the individual does not count for very much, only insofar as that individual can analyze what the controlling problem is and bring together such groups of technicians as are necessary to solve the particular parts. We are in a transition from the individual as a producer of new industries to the group. We don't know how to do group work very well.

We must get away from the early development of new industries on the basis of profit and loss; the basis of return on capital. We must think of it as the development of something in which faith, in which the rightness of the thing, becomes the important factor. We have detailed accounting in industry. Sometimes we have that same accounting applied to research and industrial development, but they cannot live under such treatment any more than you can budget your baby's bath or milk bottles.

We must treat research, therefore, as an insurance policy. Whatever we pay for that we must think of on the actuarial basis; that over a given period of time and over a fairly large number of projects enough good will come out of it to make it worth while. We have said that the depression has cost us an enormous amount of money. Nobody knows how much. Billions of dollars we are told, and yet a billion dollars a year would keep 500 or 600 research laboratories going full time, provided you could get the men. Of course, we haven't yet enough trained men to run that many laboratories; but if we had, and had them running for 3 or 4 years, the banks would have no [surplus] money and there would be no unemployment. We would have "help wanted" on every door of every factory in America. That price would be infinitely less to pay for this industrial development than trying artificially to stimulate one in which the fundamental principle is not fully recognized. You can't create unless you know what your objectives are. Simply to put people to work without having any recurring co-ordination means that when the money is exhausted you haven't anything that will go on its own power. It is up to the engineer to advise, and in this respect I think he is to blame because he has not been sufficiently active in getting his financial advisors to recognize that development of industry is as important as operation of industry. In commending this point to you, I think we all recognize that building is one of the important things of all industry. Operation is an essential, but the number of people who can be employed in operations is rather small as compared to the builders. You have to take our country by and large today and see where we are. What do we need? What would we like to have? And then sit down and say, "How long would it take us to get that? What is there in this thing that we don't know?"

Sometimes a great industry is held back for years because of some simple detail and, if we don't recognize that detail, large sums of money can be spent and no apparent progress made. When finally that last detail is supplied, the industry snaps into action and we go ahead. Almost every line of development has opportunity. If we go back and analyze our industry, say with the factors that made the motor car industry possible, we find. . . . . [that] perhaps the most important was the pneumatic tire.

If you will read the history of the development of the pneumatic tire you will read one of the most dramatic things in all industrial development. Mr. Dunlop didn't develop the tire for motor cars. His son rode to school over a piece of rough pavement on a solid rubber tired bicycle, and complained about it. His father, who was a veterinarian, . . . .made a wooden wheel and on the edges of the wheel he tacked a canvas loop. Inside of that he put a rubber tube and with a football pump he pumped it up. That was the first pneumatic tire; conceived not as a scientific invention, but something to please a small boy.

If you read the discussions in the scientific papers of the years in which the pneumatic tire was making its way on racing bicycles, because that was the only use for it—you will find very learned discussions among engineers as to the whys and wherefores, why it wouldn't work and why it would work. No progress was made until a very much unknown bicycle rider defeated the champion and then everybody said, "There must be something to it." In other words, Mr. Dunlop produced a sample, a *working* sample. I sometimes think we discuss too much and don't make enough samples whereby we can get the thing across. I am a great believer in all the formulas and other things that necessarily are used in engineering, but I feel that the fact is very much better ahead of the formula than behind it. . . . . .If you go back and trace the history of all industry, you will find that exact thing. Somebody did something that everybody was sure wouldn't work. It wouldn't work under certain conditions but the fellow who succeeded didn't do it under those conditions, he did it under slightly different conditions. . . . .So, I am for more experimental work in science. I am for bringing out or trying to convert, if you want to think of it that way, some of the intangibles of our modern science to see if we can't spin them into threads that the engineer can use and weave into our everyday work.

We are told today by very learned men that the things we do that we think are tangible are not;

that they are only a mental concept. Now that may be. We may have to have a certain kind of mind in order to believe that those microphones are immaterial, or that something I say in here is repeated to you through a loud speaker, or that this watch is simply a correlation of mental phenomena. There may be minds that can grasp that thing, but it isn't an engineer's. An engineer has to have something he can hit with a hammer. If there are some people who can conceive of these things without any material relationship whatever, I glory in their ability, but it doesn't help me a bit. I have got to have a hammer and a nail to put 2 boards together. I can't wish them together, nor anything else.

We need today to lessen that great gap that has existed and is growing wider and wider every year between the so-called pure science and applied science. We are drifting apart, and we are drifting apart for very definite reasons. The purely theoretical man doesn't like the hard-boiled attitude that the commercial engineer has to have. Therefore, when he proposes some of his schemes and he hasn't a sample, and you try them out and they don't work, he doesn't like that. Consequently, he likes to select those problems about which the commercial engineer can't ask him any questions. And the commercial engineer, because of that thing, because of the experience he has had before, doesn't want to go and ask him any questions. So, between the technical education that we have today and the practical thing, a wide breach has been developed.

We find that the younger trained engineers have been given an enormous amount more of mathematics and mathematical physics than the older ones have. I tried to find out why that is. There is nothing wrong with it at all. There is nothing wrong in the mathematical approach to any problem. The only point I raise is that it is not the only approach. Mathematics is a tool in engineering exactly like a milling machine is in a factory. Because a milling machine may be good doesn't mean that you throw out your shapers and your lathes and your planers. I think we are making the problem of doing simple things very much more difficult by trying to mathematize them than we would if we just did them.

A very great instructor in music once, when someone asked him what the word "technique" in music meant, said that it was playing the simplest passages in the most difficult way.

We have developed a lot of technique in engineering, and sometimes we make a very great and very difficult problem out of a simple one. I can't help but think that all the problems of nature are simple, and I think the difficulties we have are very largely due to our own conception of them. In the last few years there have been some very marvelous books published among which I think I remember one called "This Mysterious Universe" by a great engineering author. It is a wonderful book. It is well worth anybody's reading. I have no objection to the book at all and the contents of it. I only object to the title, which should read, "A Mysterious Mind's Concept of a Normal Universe." The universe must be normal or it wouldn't have run along so well for such a long period of time.

. . . . .Nothing can be done to keep the earth from turning around on its axis. There is nothing to do about the peculiar way it has of going around the sun, which makes the seasons. There is talk about leveling our production, and that sort of thing. The first thing we ought to do is to straighten out the earth's axis and cut out those seasons. That would help a lot, but we can't do much about it. . . . .We are going to have our seasons, and that is great for the dressmakers and everybody else, because I don't know what we would do if we didn't have some reason for changing styles. We have to take the things as they are, and we must go ahead.

Another interesting thing is that all the rest of our lives are going to be lived in the future, unless we spend too much time wishing we had lived them in the past. Therefore, I would like to make that future just about as nice a place to live in as I can think of. If we don't carry over too much of the old, dirty past; if we begin to think of a polished, bright, glistening, and glorious future and say, "Why is it, it can't be that way?" we can solve those problems, because I think we can make them anything we want.

We have a lot of things that we ought to tear down and throw away. I say we ought to rebuild this country. The first thing you know, the banker and economist says, "Where are you going to get the money?" I am going to tell you where you are going to get it: In exactly the same place we got the money to build it this far. We didn't have any to start with. All we did was dig this building out of the ground and put it up here. It didn't have to grow; it has always been here, but it wasn't in this particular shape.

We can take man-hours and convert material into almost anything we want. First of all, we get scared about what it is going to cost. The only things we have of any value in this world at all are the natural resources of the country—with which we didn't have anything to do. They were here long before we got here, although we sometimes think we created them.

We have the man-hours of intelligent, useful people, and every time you cut out a useful world of intelligent active, skilled people, that is the economic loss. Anything we do to keep materials from being converted into human utilities is an economic loss. And if materials are converted, somebody else does something else. Money is used only as the conveyor to carry it from one point to another. We have been calculating in dollars entirely too much.

The wealth of the nation is not in dollars; it is in useful material, and the positive side of economics is the movement of useful materials through the channels of trade. That must always go ahead of the return flow of money through the counting houses.

It is up to the engineer to do the positive side of the thing. For the last 10 or 15 years, I am afraid the engineers have hobnobbed too much with the bankers. The engineer is a great person in this respect, to work with the banker on this question of standardization. We had the great standardization idea that if we just got everything made alike, what a wonderful world it would be.

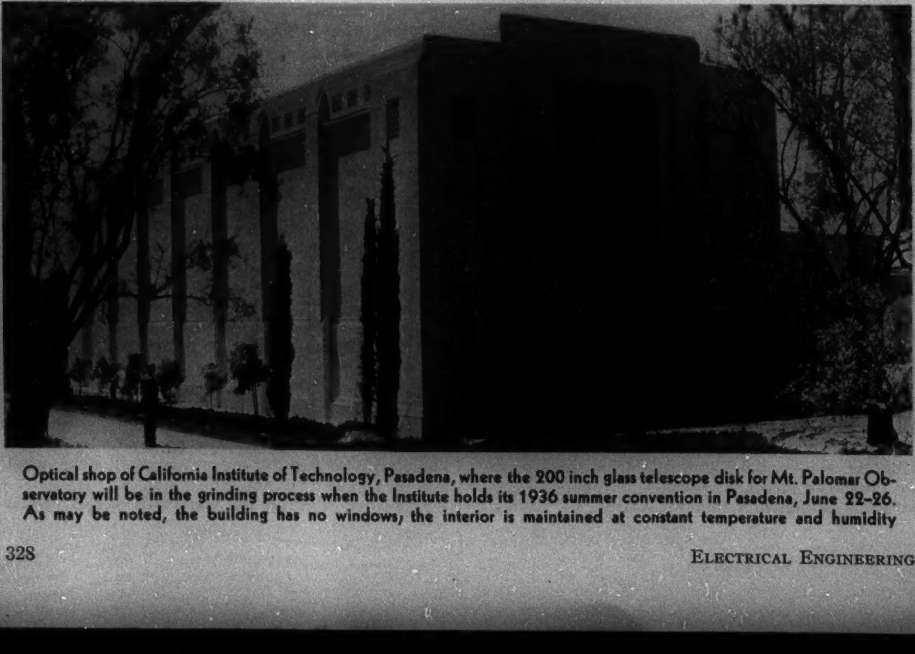
I pictured one time the marvelous day of Utopia when every engineer would have standardized everything he could think of. There was going to be a great celebration. Down the main street of the great city of Utopia we were going to have a parade, like the Mardi Gras. At the end of it we had this beautiful arch of accomplishment called "Standardization," and the band played, the floats went down, and the crowds cheered. We had arrived. But as we marched through the arch, if we had turned around and taken a look back at the other side of it, the side we forgot, we would have found that nature had slipped another motto on there that we didn't think of: "This is the land of stagnation, cut-throat price competition, and depression." That is where standardization will always lead in the last analysis.

I have no objection to standardizing the nails that go into my shoes or the buttons on my coat, but I do object to standardizing the style. If I want a coat different, with different kinds of buttons on, I want to get it. We have buttons on our coat sleeves because of habit. There is no more use for these buttons on my sleeve than there is for a rabbit having 3 ears, and yet custom and style say they go there.... They did serve a very useful purpose at one time. Our monks used to eat soup, and their long flowing cuffs got in the soup until they put buttons on and buttoned the cuffs up to keep them out of the soup. We have economies on the amount of cloth that goes in the sleeve, but we still leave the buttons. So all we need to do is go back and survey where we came from.

Remember, research hasn't anything to do with throwing away what is old; only with going back and analyzing whether the old thing may not be entirely revived in its utility by the introduction of some new things. . . . .Research, so far as engineering is concerned, is to go back and study why did we do things the way we do them, and how we can improve them. The other thing is to cut loose our imagination and do a little wishing.

What are some of the things we would like to have? Why can't we have them? Research is not a thing that goes only with a laboratory; it is purely a principle, and anybody can apply it. It is simply to try to find out if you are satisfied with what you have, where you are, and what you are doing. Write down 10 things that you don't like about your business, about yourself, or the things you are doing or working with as your problems. You may not be able to solve the number one, because it may be a very difficult thing, but you will be able to pick out one of them, just like you put the word in the crossword puzzle. Finally, after a period of time, you will be surprised to find out how these things break down if you persistently work at them. In other words, research is simply trying to step farther ahead to try to find out, as I say, what we are going to do when we can't keep on doing what we are doing now. That doesn't need to be done in a laboratory. . . . . Time is going to move on, and time is going to bring to us new things and new facilities, if we have open minds. . . . .I never at any time, even in the most prosperous times was any more confident that this country can go ahead and develop than I am now.

I think the next 10 years is going to see a complete renaissance in engineering and scientific development. It is all ahead of us. Every period in time has always had somebody to say: "I don't see what new there is to be done.". . . .If we can take out the bugaboo of "Your world is finished," and put instead of that "The world is begun," we have a marvelous place to live and a marvelous future ahead of us.



**Optical shop of California Institute of Technology, Pasadena, where the 200 inch glass telescope disk for Mt. Palomar Observatory will be in the grinding process when the Institute holds its 1936 summer convention in Pasadena, June 22–26. As may be noted, the building has no windows; the interior is maintained at constant temperature and humidity**

# The Young Engineer
## Under Changing Conditions

**The situation in which the young engineer may expect to find himself under currently changing conditions in industry is discussed in this paper. Also, the education of engineers, undergraduate and postgraduate, is reviewed from a practical point of view in the light of circumstances likely to be involved in their early activities in industry. Suggestions are given concerning undergraduate curricula, and concerning educational activities that could be carried on to advantage by the young engineer after entering industry. The necessity for a proper balance in various activities and in personal characteristics is emphasized.**

By
**R. E. HELLMUND**
FELLOW A.I.E.E.
Westinghouse Elec. and Mfg. Co., E. Pittsburgh, Pa.

So MUCH has been written during recent years concerning changes in engineering education and the position of the young engineer in industry that it is with hesitancy this paper is prepared discussing the subject further. Nearly every conceivable idea has been advanced for adapting matters to changed conditions (see reference list) so that almost anything now offered can be merely a repetition of thoughts previously expressed. In particular, the very excellent paper by President C. C. Williams of Lehigh University, "The New Epoch in Engineering Education,"[1] which came to attention after this paper was outlined, has increased this hesitancy because the ideas involved are in substantial agreement, particularly on a good many points regarding the college curriculum. Therefore, such thoughts as are set forth in this paper are submitted principally for the interest they may have as emanating from one who is not directly connected with educational work, but who has been closely associated with many engineers engaged in research, design, application, and other project work, and who has had an opportunity to observe at close range their performance, their mental attitude, and possibly their shortcomings during periods of prosperity and depression alike. If certain conclusions arrived at from this position of observation, which naturally differs appreciably from that of the educator, are in agreement with his, this should encourage procedure at least along the lines of agreement.

In discussing the various questions, it is not the intention to act as a prophet or to suggest any ideas that will lead to the millennium, but rather to examine from a practical point of view conditions as they now are and as they are likely to be in the near future, and from this to reach some definite conclusions.

### Undergraduate Preparation for Engineers

The extreme maladjustments brought about by the depression have resulted in suggestions for rather radical changes in engineering education and, as in many other matters, a tendency has developed to discard the good with the bad and to lose sight of the fact that there are certain fundamentals that will hold regardless of business cycles. It has been suggested that, since the engineer was somewhat responsible for technological unemployment, his college education should be broadened to such an extent as to enable him to avoid or remedy all the social evils having any connection, however remote, with engineering work. Although the writer has given it serious thought during the depression, no one thing is known that the individual engineer or any group of engineers could have done to ward off the depression or to restore conditions to normal even if their education had been such that they had fully understood all the factors entering into the situation. Even if it were desirable, for the good of humanity as a whole, to retard the introduction of laborsaving designs and devices with the idea of avoiding technological unemployment, an engineer employed in any competitive industrial enterprise has no choice whatsoever but to do everything in his power to reduce costs if his concern is to survive and continue to provide employment. Since even the most ardent advocates of government control of business in the United States have never suggested the elimination of competition in industry, an early change in this situation cannot be expected. The only way in which the engineer can contribute toward increasing employment is to continue to create new products for which there is a need or desire, and to reduce the cost of products already in use so that a larger percentage of the population will be able to buy them. The only conclusion that can be drawn from this is that the future engineer must prepare himself to do more and better engineering and that any attempt to delete from the engineering curriculum any subjects that are necessary for successful engineering in order to make room for more or less unrelated subjects is a step in the wrong direction. Another practical and important consideration supporting this latter point of view is that the majority of the younger engineers enter married life soon after graduation and must therefore be in a position to earn a reasonably satisfactory living. Industry, although in general very willing and anxious to help the young engineer in his further

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[1] For all numbered references see list at end of paper.

education, can hardly be expected to support him for several years without obtaining reasonable service for the salary paid to him. Therefore, the young engineer should enter his profession with at least a thorough knowledge of the essential fundamentals relating to his particular engineering work.

The previous conclusion that the future engineer must do more and better engineering has been arrived at chiefly from consideration of the engineer's relation to his business and to social problems, but it also seems to be the best way to raise the engineering profession to a higher level in society, which, of course, is the desire of every true engineer. In judging a physician or lawyer we do so by the ability of each within his own profession, and in evaluating the standing of either of these professions in society we naturally do it by the accomplishments of the profession as a whole. Similarly, the engineering profession will be measured by its accomplishments in engineering. Assuming, then, that undergraduate education should strive primarily to produce good engineers, the question might be asked: In what respect could the curricula of the engineering schools be changed better to accomplish this purpose?

In observing engineers in their work in industrial organizations, the most obvious shortcoming noted is that they frequently become so absorbed in the solution of an interesting problem that they fail to pay sufficient attention to certain economic and commercial features. This point, while not new, has been brought to the foreground by conditions during the depression that made it more necessary to focus attention upon the economic phase. The writer is therefore in accord with the suggestion made by many that economics be afforded a more prominent place in engineering education. In many college curricula, courses in economics are included, but are given by the department of economics. Some of the basic laws given to engineering students in this manner may be of value, but much of the work covered at present is far removed from the practical applications encountered by the engineer in his work. Hence it seems that the engineering schools should offer some courses in economics and their practical application.

Psychology is another subject of study that for several reasons will assist the engineer in effectively carrying on his engineering and related activities in modern industry. With the increase in industrial organizations and the necessary specialization and departmentalization, work cannot be performed effectively without a thorough knowledge of human nature. This again is not new, but the importance of it has been emphasized by the depression. Whenever reductions in force were necessary, the deciding factor in the release of one rather than another was frequently some personal shortcoming rather than a lack of technical ability. For details, reference might be made to an interesting study by T. Spooner.[4] Although the study of psychology by no means will correct all personal shortcomings, it nevertheless seems to be the only practical means by which the colleges can bring about improvement.

Another circumstance making desirable a greater knowledge of psychology is the increasing sale of technical products to the public at large. During the early days of engineering, activities were confined chiefly to technical accomplishments, such as the building of bridges, railroads, tool machinery, electric generators, motors, and the like, in which the engineer designing these items usually had to deal with customers who also were technically informed, and in which the considerations involved related principally to such features as technical utility. At that time the industrial products intended for the public at large were very simple and were designed by artisans rather than by engineers. During more recent years many such devices have come into existence that in their design require technical skill and a great amount of theoretical knowledge. Examples are: the modern household refrigerator, automatically controlled electric heating devices, air conditioning equipment, and so forth. The engineer taking up this work, although well trained to handle the purely technical features, generally is not prepared to appreciate fully the psychology of the public as the purchaser of such items. By sheer necessity many engineers in industry have been forced to acquire knowledge along this line, but little attention has been given by the colleges to these changed conditions. In dealing with the public at large the problems to be considered are partly of an economic nature, which again emphasizes the necessity for paying more attention to this subject. In addition, there is a great need for a knowledge of the psychology of the buying public. The total expenditure which most people can make is definitely limited and therefore it is essential to learn as far as possible what the various classes of people will be willing to spend their money for, and what prices they will be willing to pay for conveniences and luxuries that industry can make available to them. Again, in connection with well established articles which the public buys regularly, it is essential to determine which of the various improvements possible will be accepted by the public at the additional cost necessary to include them. Since it is usually the engineer who conceives new articles and new features in existing articles, it is very important that he acquire some knowledge of the public's attitude toward these.

Although it is self-evident under present day conditions, it is mentioned here principally for the sake of completeness that psychology is of importance to the engineer working with the public utilities, because of the increased importance of public relations; to the sales engineer in his contacts with customers; and to the works engineer in his labor problems. As in the case of economics, the teaching of some of the more fundamental principles of psychology may well be left to the department of science, but again it seems desirable that various specific courses having close relation to engineering be given by the school of engineering and be made available to engineering students as elective subjects.

In addition to the many suggestions for broadening engineering education, there have been during recent years many suggestions for new engineering courses and for further subdivisions of those existing, the idea in general being that there should be one course for the students who wish to take up research and technical engineering work and other courses for those wishing to assume administrative duties, sales work, and the like. Although eventually some more complicated classification of this nature may be worked out, it is believed that steps along this line at this time would be premature. One reason for this is that few courses are now available on the individual subjects, such as engineering economics and psychology, that have a substantial content of analytical methods useful in solving practical problems. A great many schools have introduced certain so-called industrial engineering courses, but in many cases these do not have the same standing in the minds of employers as have the courses in electrical, mechanical, and civil engineering for example. Furthermore, at some of the universities there is a feeling among the students that these industrial courses are the ones that make it easy to obtain an engineering degree. This, I believe, is due entirely to the fact that industrial courses were set up in many instances without sufficient background of subjects of practical value. Progress has been made in this direction and some books have been published on industrial economics, but at present most of these books, although containing interesting historical accounts or setting forth existing conditions, give very little that is of assistance in analyzing industrial economic problems. Courses in engineering economics and various courses that may be devised for the application of psychology to engineering activities no doubt will be very difficult to initiate because of the lack of material and also of teachers able to handle these subjects. For this reason these courses should be introduced as elective, and not until they have proved their worth should any attempt be made to introduce them as compulsory, especially where this would mean the elimination of other well organized courses now being presented. For the present it seems best that those students wishing to carry on the engineering of transmission projects be given an opportunity to take an elective course on transmission calculations, while other students who intend to enter the merchandising field either as engineers or salesmen be allowed to select a course on the psychology of the buying public. Again, students wishing to go into the design or manufacture of engineering products used in industry should select a course in engineering economics.

Another reason why it would be inadvisable to start several subdivisions of engineering schools, as, for instance, courses for engineering economists, is that industry is hardly ready to take on such specialists. One of the most important lessons learned by industry during the depression was to make all possible efforts to hold overhead costs low. Some of the larger concerns are experimenting on a small scale with offices or bureaus handling certain special work, such as economics or market analysis for instance, however, it is evident that in the beginning such work cannot be intrusted to young graduate engineers inexperienced in present business methods, but will have to be carried on by older employees. Part of such personnel may not even be engineering graduates, though a few engineers may be called upon to handle some of the work of a more technical nature. Most of the smaller concerns will not for some time to come undertake market or economic studies of any kind. Even in the larger concerns there is a definite tendency to avoid additional functional specialization whenever it is at all possible. Furthermore, economic questions relating to engineering activities usually are tied in so closely with engineering work proper that it is impractical to have them handled separately by special personnel. The engineer himself or his supervisor must give these matters the necessary attention; in other words, what is needed in the majority of cases are engineers who are economically and commercially minded rather than specialists in engineering economics. Concerns manufacturing highly technical products, as, for example, electric machinery, at present prefer to employ even in their sales departments graduates of engineering schools, because their salesmen have to deal constantly with technically trained customers. It must be realized that these salesmen must be able to discuss engineering problems intelligently and that they will have but little opportunity for education in engineering fundamentals except while in college. They of course also need a thorough knowledge of psychology and economics, and their needs would be well served if in addition to the basic engineering subjects they were given an opportunity in college to take elective courses in engineering economics and psychology instead of some of the more highly technical elective courses now forming part of the electrical engineering curriculum, but of value only to those wishing to take up highly technical work.

## GRADUATE COURSES PRIOR TO ENTERING INDUSTRY

As the writer frequently has stated, it is believed that it is somewhat dangerous for engineering students to stay too long in the college atmosphere. The engineering profession is one of accomplishment, requiring initiative and aggressiveness, traits which are not so likely to be developed in college life, particularly in the type of students most inclined to take postgraduate work. Therefore it seems to be better for the young engineer to enter industry as early as possible after completing the undergraduate course. The present undergraduate courses, modified as suggested to permit greater freedom of choice in elective subjects, will equip engineers satisfactorily for more than 90 per cent of the positions they will be called upon to fill in the beginning. There is no doubt that for certain types of highly technical and research work some postgraduate work at a university may be desirable, especially if the students are unable to find employment in localities where opportunities for further education through courses given by the industries or night courses by colleges are available. If for this reason postgraduate work is carried on at college, or if it is taken up because graduates cannot find immediate employment after graduation as has been the case during the depression, it is advisable to take courses which will be of assistance in engineering work but which do not directly relate to the specific type of engineering contemplated.

Knowledge of such related subjects usually is harder to acquire later on than subject matter directly related to an engineer's work. For example, an engineer wishing to enter research work on electrical subjects will do well to take additional mathematics, physics, physical chemistry, etc.; an engineer wishing to take up practical design will find additional work relating to the materials used in his type of engineering, such as chemistry and metallurgy, very useful. Frequently some postgraduate work at a university after a few years of experience in industrial research is of advantage because the engineer then is in a better position to judge what line of study will be most helpful to him.

### OPPORTUNITIES FOR THE YOUNG ENGINEER IN INDUSTRY

At present the most vital and at the same time the most difficult question to answer is: What opportunities exist for the young engineer in industry? To gauge these possibilities, it seems necessary to review some of the past. In looking back, statistics show that during the boom period preceding 1929 there were about 10,000 engineering graduates annually, of which 5,000 were electrical and mechanical engineers. More than half this latter number were absorbed immediately after graduation by 3 large electrical concerns. Even allowing for the fact that a few of these men later on became available to the utilities and other manufacturers, it was very difficult to see how these few together with the other half of the 5,000, could even approach the needs of the other electrical manufacturing concerns, public utilities, and the vast number of industries engaged in mechanical engineering work. In fact, at that time it looked as though a good deal of engineering work was being done by men without any or with only partial college training, and, as is well known, some of the needs were being filled by foreign trained engineers. It was quite natural under these conditions that considerable competition arose among the larger manufacturing concerns for the services of at least the better graduates of engineering schools. On the whole, there was much evidence of a shortage rather than an oversupply of good graduate engineers. Even at that time many university graduates were drifting into positions that could have been filled by technicians trained in schools requiring but 1 or 2 years of training; however, such activities probably always will be an outlet for some of the poorer university graduates who either lack the mental ability or the ambition to work up to higher levels of engineering work.

During the depression the business of many industries decreased to anywhere between 20 and 60 per cent of previous levels and, particularly in the heavy industries, where engineering is of greatest importance, it reached the lower of these levels in many instances. It is therefore not surprising that engineering forces had to be radically reduced, leaving great numbers of experienced engineers without employment, and that during the lowest level it was practically impossible for engineering graduates to find employment. At present, business is noticeably on the upswing, but because of many uncertainties industry is increasing its forces very cautiously and not in line with the increased amount of business. However, all indications are that as time goes on further need for additional engineering talent will arise and employment will have to be made at an increased rate. In meeting this situation, industry can choose between young graduates and some of the older engineers who are still unemployed; in other words, the young engineer will have to consider these older men as his competitors. Some of the older men have been permanently retired and pensioned and others have taken up activities other than engineering; in the latter case also the change in many instances will be permanent because some of these men are better suited for other activities and will remain in them. This, of course, is fortunate for the young engineer, particularly since men from other professions are not likely to drift into engineering because of their lack of special training. Nevertheless, there still are many engineers unemployed and others ready to return from other activities to engineering work. Should business pick up rather quickly at any one time, employers will have no time to train new men and therefore will re-employ some of the older men experienced in the particular work to be performed. However, with the exception of those cases where talent with specific experience and ability is needed at once and is available, the young engineer has the advantage in practically every respect, for the following reasons:

1. Most employers appreciate that the best results can be obtained only by maintaining a proper balance between older and younger personnel. The older generation is needed for its experience and mature judgment, while the younger is needed to supply enthusiasm and aggressiveness. The latter qualities may be particularly helpful after this depression, when many of the older men may have become overcautious as a result of their experiences during the depression.

2. During the depression it has happened that whenever reductions in force were necessary, more of the younger employees were released than of the older ones and as a result the average age in a good many organizations has been considerably increased. This in turn means that a good many of the leaders who are still active at this time will soon drop out, making it particularly desirable that younger men be trained to take their places.

3. There is a general trend toward earlier retirement in the United States, approaching conditions in other countries where pensions have been established for an earlier retirement age.

4. Except where specific experience is quite essential, older employees usually prefer as their assistants young men with flexible minds and greater adaptability.

5. The younger men generally can be secured at lower rates.

6. In engineering there is one particular condition which at all times, and particularly now, favors the young engineer. The older engineer, although having accumulated experience and judgment, usually grows a bit rusty on his theory as time goes on and depends to a great extent upon the younger engineer, just out of school and fully familiar with the latest theories and methods, to handle the technical details in calculation, laboratory, and similar work.

The first 5 of the above items cover conditions which favor the young engineer, but over which neither he nor the schools have any control. The last item, however, which is of particular importance, is within their control, and it is one more reason why the young engineer, if he wishes to prove of maximum value to industry and to enhance his chances for early employment, must be well grounded in basic and engineering theory. This does not necessarily mean that all the tasks he will have to perform during the early days of his professional work will be of a theoretical nature, but rather that he should be ready to do work of this character when called upon to do so.

Though at the beginning of the paper it was stated that no prophesying was to be done, the writer is reasonably confident that the time is not far off when most of the better and medium graduates of engineering schools will find employment in their own profession; further, that those who are not successful in finding employment within the engineering profession and who engage in other work will never regret having an engineering education because it will prove of value in almost any work they may enter.

## THE YOUNG ENGINEER AFTER ENTERING INDUSTRY

Under the previous heading it has been definitely pointed out that there will be a place for the younger engineer in industry. After he has found employment, his progress is largely a matter within his own control. Unless he is exceptionally brilliant, he cannot expect anything but a mediocre position and remuneration if he is not willing to continue some study. The need for continued education has been stressed so much during recent years that it hardly requires any further emphasis. The nature of his continued study of course will depend upon circumstances, such as the needs indicated by the immediate and contemplated activities and the available opportunities. The engineer by this time should have a better idea of the particular work he is likely to follow than he had in school, and thus should be in a position to plan his further educational work accordingly. In prosperous times the young engineer usually has a reasonable chance to enter the kind of engineering work he prefers, but in the days just ahead he may not find it advisable to be too "choosey." Even in normal times he may be compelled to take up work somewhat different from his first preference. Because universities give extensive courses on power generation and transmission and practically nothing on technical merchandising devices, and also because of the inclination on the part of youth to do big things, about 70 per cent of all engineering graduates usually express a desire to go into power transmission work, the design of large machinery, railway electrification, and similar work. Of course it is not possible to employ such a large number for work of this nature, and therefore it has been necessary to persuade some of these engineers to take up other activities. Practically no instance is recalled where these men later regretted their action as they soon learned that there are very interesting problems in almost any engineering and related work. For this reason, the young engineer need not be particularly concerned about having to enter work not entirely in accord with his wishes, but rather he should prepare himself to handle effectively the work assigned to him or any to which it may lead.

A brief outline of the type of courses usually taken by the engineering graduates during the early years of their employment with the company with which the author is associated may be of interest. Research and design engineers take certain courses dealing with the application of the fundamentals to practical problems. Later on some of them take advanced courses in the analytical treatment of the more difficult problems. Courses on differential equations, advanced physics, and, more recently, on metallurgy, engineering economics, and the like have been made available. Sales engineers are often not in a position to carry on educational work at headquarters over extended periods of time because many of them are assigned to district work after a period of training. During this time they frequently take one course in the application of fundamentals to practical problems, similar to that taken by the research and design engineers, and other courses relating to commercial activities, industrial economics, and psychology. In addition, some courses on engineering subjects definitely prepared for the purpose are made available to sales engineers in the field, either as correspondence courses or through class work given by older district engineers. Engineers entering the works organization take courses on industrial economics, metallurgy, time study, and other subjects of interest. Also, courses on various languages and public speaking are available to all engineers. The greater part of this work, particularly the subjects for research and design engineers, is handled through the co-operative graduate course carried on jointly by the University of Pittsburgh and the Westinghouse Company and described more in detail in a previous paper.[9]

As a rule, engineering graduates are advised to take first the more difficult scientific and technical courses, as it will be much more difficult for them to take these courses later on when they are under greater stress from their regular work, and also because of demands upon their time by newly acquired family ties. This latter condition is one that often is overlooked in discussions on postgraduate engineering education, but it is one of practical importance in many cases.

Although in the foregoing, engineering education for engineers has been stressed chiefly for practical reasons, the writer does not wish to be understood as believing that broader education and a broader aspect of life should not be striven for by the engineer. The writer does believe, however, that the purpose of the broader interests should be to enable him to live a richer and fuller life rather than to enable him to remedy all the evils and maladjustments of the day. It is highly desirable for the engineer, after disposing of the most essential factors necessary for him to earn a satisfactory living, to make every effort possible to broaden his education and point of view. At present unlimited opportunities are available for this purpose.

Frequently the younger engineers ask the question: What makes the successful engineer? Obviously it is impossible to answer this by any general statement, because engineering work extends over such a variety of activities that certain qualifications of prime importance in some activities may not be essential in others; even for a specific type of engineering, so many different qualifications are required that a reasonably comprehensive answer would require extensive discussion. However, there is one general principle which the engineer should try at all times to follow, and that is to strike the proper balance in both his personal characteristics and his engineering activities. Like most fundamentals, this is not new, but the importance of it has been emphasized during the depression, when it seemed that those engineers who maintained this proper balance in general fared better than others.

Assuming that this principle of proper balance has been applied to the various studies carried on by the engineer, the next and most important thing for the engineer to realize is that in the final analysis he will be judged by what he can accomplish rather than by what he knows. Therefore, although the acquisition of knowledge as a tool is essential, the engineer after entering industry must guard against devoting so much of his time and attention to additional studies that he neglects actual accomplishment. It is only through a proper balance between these that he will succeed. This same principle applies to nearly everything entering into an engineer's activities. Naturally, to be a successful engineer, he must have many new ideas, but at the same time he must not start work on so many of them that he cannot bring any of them to a successful conclusion. An engineer must be forward-looking, but even here he should devote his attention to matters that are possible of practical realization within a reasonable time. It has been frequently stated by Dr. Kettering, of the General Motors Corporation, that the important qualification of a research engineer is a continued state of dissatisfaction with present conditions. This undoubtedly is true, but this should not be carried to the point where the good of the present order is discarded with the bad. The engineer unquestionably should strive for perfection in his work, but at times it is impractical to strive for a degree of perfection that is not attainable within a reasonable period of time and at a reasonable cost. A good deal is heard about the need for specialization, and often in solving specific problems specialization is necessary, but if he wishes to retain a broad viewpoint the engineer should be careful not to carry this too far. Generally it is desirable to attack the more involved engineering problems from a theoretical and analytical point of view, but this may prove a waste of time when ordinary reasoning and common sense plainly indicate the course to be pursued. Furthermore, if he wishes to avoid the reputation of being a theoretical dreamer without a practical point of view, the engineer who has cultivated the ability for theoretical work must be careful not to overlook relatively simple matters of practical importance. Most new engineering undertakings require a great deal of optimism, courage, and perseverance if success is to be attained, but this should not prevent the engineer from critically examining his work in order to make sure that he is not spending a great deal of effort on projects that are not possible of accomplishment at the time, or the economical importance of which is out of proportion to the effort and expense necessary to accomplish results. Examples of this kind could be continued indefinitely, but those that have been touched upon briefly should be sufficient to illustrate the absolute necessity for striking the proper balance in everything; which, of course, also means that the engineer must try to cultivate those characteristics in which he finds himself lacking.

This paper deals principally with the young engineer's training and early activities in industry, but as a matter of course his chances for future advancement must always be kept in mind. Many engineers will prefer to continue in highly technical or research work and they will find satisfaction and reward in the national or international reputation they obtain within their profession because of leading work in their line. It is evident that the technical and scientific training advocated in the paper is the most suitable for their purpose. Other engineers, preferring to work toward executive positions, will find that in addition to a sound technical training and a habit of analytical thinking they must very early adopt a definite plan for broadening their interests to include commercial, administrative, and many other subjects relating to business in general. Of course, personality, a certain inborn ability for leadership, and similar traits are prerequisites for success along these lines.

In concluding, there is nothing better than to quote President E. B. Meyer of the A.I.E.E., in his message on the subject, "Opportunity and the Young Engineer," appearing in the November 1935 issue of Electrical Engineering, in which he says: "The question of opportunity for the young engineer is simply the question of his scientific training, plus initiative, aggressiveness, character, personality. Good men are needed now as they always will be."

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# Electrical Apparatus for Diesel Cars and Locomotives

**Rotating apparatus for Diesel-electric cars and locomotives is described in this paper, and certain design and operating data are discussed.**

By
G. F. SMITH
ASSOCIATE A.I.E.E.

Westinghouse Elec. and Mfg.
Co., E. Pittsburgh, Pa.

ON Diesel-electric cars and locomotives the principal functions of electrical transmission are:

1. To transmit power from the engine to the driving axles.
2. To vary the ratio of the engine speed and torque to the speed and torque required at the driving axles.

Additional purposes are:

3. To supply electric power derived from engine power for the operation of auxiliaries such as compressors for air brakes and air conditioning, blower motors, locomotive and train lighting, and battery charging.
4. To start the engine using the battery as a source of power.

Electric transmission can be utilized to transmit the power of the engine to the driving wheels and to permit its use over as wide a range of speed as service conditions require. The curves of figures 1 and 2 show typical results with electric transmission as compared to mechanical transmission. No mechanical connection between the engine and driving wheels is necessary with electrical transmission. The engine drives an electrical generator and the power is conducted by wires from the generator to the motors which are geared to the driving axles.

In figure 3 is shown a simple diagram of the electrical transmission. The generator field may be excited in one of several ways as will be discussed later. The motors are arranged in 2 groups which may be connected in series or parallel, and arrangements are provided for weakening the fields of the motors, usually by shunts, in one or more steps.

### MAIN GENERATOR

A typical engine-generator set is shown in figure 4, while desirable generator characteristics are indicated in figure 5. The generator size is primarily a function of the capacity and speed of the engine. From figure 6 can be determined the required speed for any given engine horsepower with which a certain generator weight per horsepower could be obtained.

The generator rating usually is based upon its continuous kilowatt capacity corresponding to the engine capacity. Generator voltage can be selected to give the most economic design of generator and motor combination, without reference to some standard trolley voltage. This freedom permits the designer to pick a "natural" voltage instead of an arbitrary voltage. To avoid a multiplicity of voltages, it appears desirable to establish certain standard voltages which can be used in ratings. The following voltages in uniform geometric steps cover the necessary range: 1,000, 800, (750), 640, (600), 500, 400, (375), 320, (300), 250. The figures in parentheses are values proposed in the new A.S.A. rules to conform to existing standards.

The ampere rating of the generator will, of course, follow from the kilowatt capacity and the voltage, and will be discussed more fully later as regards its relation to the motor ampere capacity.

To obtain a range of operating speed within the continuous capacity of the generator, it is necessary to have a range of voltage within the continuous capacity. As noted from the curve of figure 5, an overvoltage of 25 per cent is considered desirable, the use of which will be discussed later. The maximum ampere capacity of the generator as indicated on the curve is 160 per cent of its normal capacity. With series-parallel control of the motors, this overload capacity is sufficient to provide for any necessary motor overload. The maximum capacity of the generator in relation to continuous capacity, from the standpoint of both commutation and heating, is more limited than in the case of the motor. When carrying the maximum ampere load, the generator may be operating at full engine speed, whereas the motors at maximum ampere demand are operating at greatly reduced speed. Since the commutating voltage is proportional to the ampere load times the speed, it readily may be seen that the motors are much less limited in this respect than is the genera-

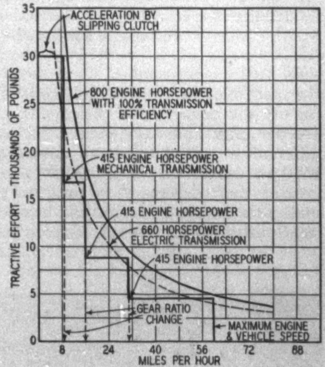

**Fig. 1. Comparison of speed-tractive effort characteristics for electrical and mechanical transmissions; 800 engine horsepower**

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tor. Likewise, the generator usually is operated at a higher speed and is more open, and hence more effectively ventilated than are the motors. Therefore the generator is smaller and lighter than the motors, thus reducing its thermal capacity and its maximum load capacity.

## METHODS OF CONTROL OF GENERATOR FIELD

*Differential Field Generator.* To secure as nearly as possible the ideal generator curve as given by figure 5, various methods of automatic regulation have been used. Inasmuch as the generator field current should be reduced when armature current increases, differential field coils have been used on the main generator. The field coils of such a generator occupy considerable space. For example, with 100 per cent separately excited field and 20 per cent differential field at full load, the net field excitation is 80 per cent, whereas the space taken is 50 per cent greater than necessary to produce the flux. This makes the generator larger and heavier. By using a small differentially wound separate exciter, a generator with a field of normal size can be used. It may be noted, however, from the curves in figure 7 that while *ordinary* differential field arrangements give the *general* characteristics desired, the shape of the curve does not match the ideal.

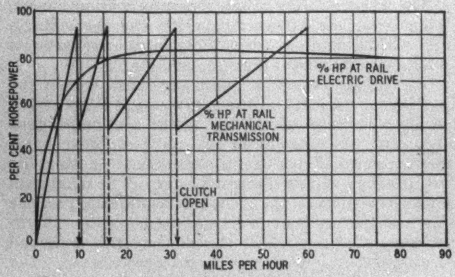


**Fig. 2. Comparative horsepower-speed characteristics of mechanical and electrical transmissions; 800 engine horsepower**

*Special Differential Exciter.* Various methods for obtaining better performance have been evolved. One of these is to use a special exciter (U.S. Patent 1,730,340) the performance of which is indicated in figure 8 and the plan of connections in figure 9. It may be noted that all poles are excited from a separate source, and that the differential field is used on 2 poles only. The number of turns in the separately excited field coils on these 2 poles may differ from those on the other poles and thus be made to furnish sufficient excitation to saturate the magnetic circuit of these 2 poles. The differential field not only reduces the field produced by the separate excitation, but at heavy loads reverses the flux and saturates the 2 poles in the opposite direction; thus bending the curve up to give the desired characteristics. The armature is wound with an ordinary 2 circuit winding, and the armature voltage is a resultant of the voltage induced by all poles. By proper proportioning of the various fields and the magnetic circuit, and taking into account distortion, it is possible to approximate closely the characteristics desired. The performance of a generator using such an exciter is indicated in figure 10.

In service, the condition of the engine, and hence its performance, will vary. In case the engine is not able to carry its load, the tendency will be to run slower. With the differential exciter scheme the slowing down of the engine will slow down the exciter and hence reduce the exciter voltage and main generator field, thereby reducing the torque demanded from the engine. This tends to avoid "killing" the

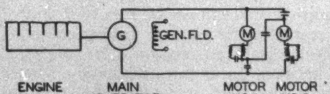


**Fig. 3. Simple diagram for electrical transmission of engine power to driving axle**

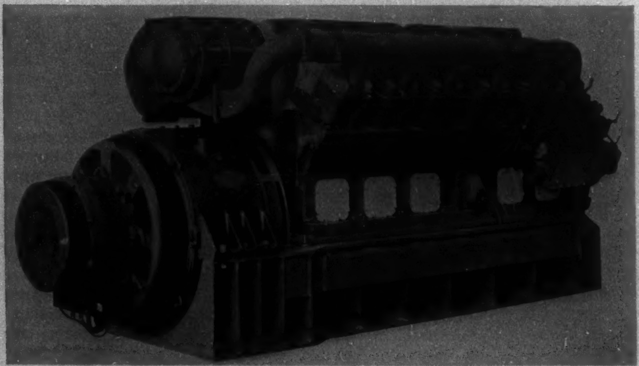


**Fig. 4. A typical engine-generator set showing main and auxiliary generators**

engine. In starting with a cold generator and exciter the resistance of the fields will be low, thus tending to overload the engine which in turn will cause it to run slower. Usually, however, the engine room can be kept warm; further, the field coils do not become heated to a very high temperature in regular service.

Where the separately excited field of the exciter is furnished by a battery, a variation in battery voltage will affect the load on the engine, a weak battery tending to reduce the load on the engine. It is very desirable, therefore, to keep such a battery in uniform condition. A small variable resistor inserted between the exciter armature and the generator field can be used to adjust for engine and battery condition and field temperature. Usually, however, such adjustments are considered undesirable unless made automatically.

*Generator Without Exciter.* For small, high speed generators, a small separately excited teaser field and a shunt field can be used. If such a machine is carefully proportioned and the magnetic section worked at low flux density, which may be desirable on such machines, the voltage will vary rapidly with the speed, and hence a slight change in engine speed will vary the generator voltage and load, and a stable condition will be reached for each load with very little change in engine speed or power. This arrangement, however, also is subject to variations in engine condition, battery condition, and main field coil temperature.

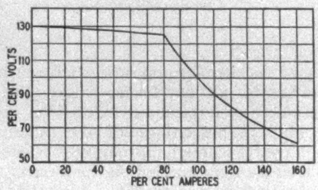


**Fig. 5. Desirable volt-ampere characteristics for main generator**

*Generator With Torque Control.* The generator field also may be controlled by a very sensitive relay connected across the armature of a self-excited auxiliary generator. Any variation in engine speed will affect the auxiliary generator voltage and, in turn, the relay. The relay operates a contactor which cuts resistance into or out of the generator field circuit. A "door-bell effect" is introduced into the circuit so that the contactor vibrates rapidly. This together with the magnetic inertia of the generator fields results in a steady voltage corresponding to the ampere load. With this arrangement, the full torque of the engine, which it can deliver at any engine speed, can be used regardless of engine condition, battery condition, or temperature of the main generator field. The effect of variation caused by temperature changes in the auxiliary generator field is minimized by winding the field for low voltage and using in series with the field a resistor having a negative temperature coefficient.

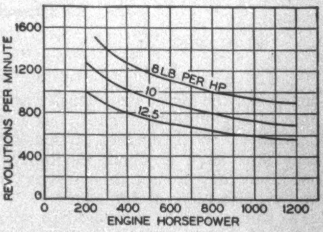
The generator excitation can be carried up to its maximum economical limit, resulting in a generator of minimum weight, and the ideal generator characteristics as shown on figure 5 can be obtained.

A motor operated face plate rheostat controlled from contacts on the engine governor has also been used instead of the vibrating contactor, resistor, and relay.

## Efficiency of Generator

Inasmuch as the engine capacity is limited, the transmission of power to the wheels with a minimum loss is especially desirable. Since generator voltage is reduced on an overload, the per cent resistance drop becomes very high and it is essential to reduce the resistance to the minimum. The resistance loss can be reduced by increasing the number of poles. However, the increased number of poles increases the frequency and hence tends to increase the core loss; thus it becomes necessary to use all possible means to reduce the core loss, which includes band losses, pole face losses, and eddy current losses. Band losses can be reduced by the use of nonmagnetic bands on the end windings and wedges in the slot. Eddy current losses can be reduced by suitable arrangement of the armature conductors. Pole face losses can be reduced by proper lamination of the pole punchings. Generators having 8 poles have come into common use in the larger sizes instead of 4 pole generators. The use of series-parallel control of the motors makes it unnecessary for the generator to carry heavy ampere overloads, and hence the generator can be operated near its point of maximum efficiency. With the larger sizes of generators, an efficiency between 93 and 94 per cent has been obtained.

**Fig. 6. Operating speeds required to give certain generator weight per horsepower**



## Mounting and Connection to the Engine

In most cases, both the engine and the generator are mounted on a bedplate and connected by a solid coupling. One generator bearing normally is used. A 2 bearing set has the advantage that the generator is a self-contained unit and can be handled readily. However, the single bearing generator enables weight to be saved and, being more open, allows better ventilation. To save some of the weight of the bedplate, the engine in some cases is arranged to be bolted to the rear end of the generator through a flange on the frame, 2 feet being provided on the generator and one on the engine giving a 3 point support.

Satisfactory results have been obtained also with single bearing machines with flexible couplings to the engine shaft. Such couplings when used with engines of the larger sizes usually are flexible to take care of slight misalignment, but have no torsional flexibility. With engines of smaller size, couplings that also have torsional flexibility sometimes are used, but they are not as rugged as the solid coupling and require more maintenance.

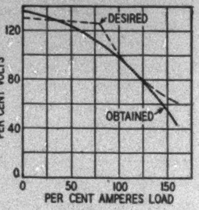


**Fig. 7. Performance curves for differentially wound generator**

In some cases, it is desired to operate the engine below the principal critical speed to avoid the use of vibration dampers. To do this, it is necessary to raise the critical speed by the use of a very stiff engine crankshaft and a very stiff connection to the generator armature. In this case, the connection is made direct to the armature spider, which is of a very stiff design.

### MAIN MOTORS

A typical motor is shown in figure 11, and typical motor characteristics, with curves at several voltages with full field strength and curves at the higher voltages with weakened field, are shown in figure 12. The maximum voltage for which the motor is suitable depends upon its commutating and flashing characteristics. The maximum commutating voltage is proportional to the product of the amperes times the speed, and hence occurs on the weakest field at the point of maximum voltage and full load from the generator. It will be obvious that the motor can be operated at lower voltages with reduced capacity, but the speed on the weakest field can be maintained by increased shunting of the field. In normal applications, and with full engine output, the motor develops 80 per cent of its maximum speed on weak field with maximum generator voltage. With the continuous generator voltage 80 per cent of the maximum, the speed on full field will be 40 per cent of the maximum. This gives a ratio of $2^1/_2$ to 1 between the maximum speed and the continuous rated speed of the motor. By operating the motor at lower voltages, the continuous rating speed is reduced and the required horsepower of the engine is reduced, the weight of the motor per engine horsepower is increased and the speed ratio is increased. The curve of figure 13 shows the weight of the motor per engine horsepower as a function of the speed ratio. This curve will vary slightly with the size of the motor, and is based upon the present A.I.E.E. rules. The proposed new A.S.A. standards permit operation at higher temperatures with class B insulation. These higher temperatures have been recognized for some time as being more conservative than the older class A temperatures used with class A insulation. The new basis of rating will result in motors of lower weight per horsepower and relatively more conservative temperature rises.

As may be noted from the generator curve, the voltage drops as the current is increased. In switcher locomotive service the motors usually are operated intermittently at overloads. Since the motor copper loss varies with the square of the load, it becomes rather high in percentage of the power available, which of course is much more limited when obtained from a Diesel engine carried on the locomotive than when obtained from a trolley. This indicates the desirability of low copper loss for motors used with Diesel-electric equipment. It should be noted that low resistance does not necessarily mean low copper loss, since the copper loss depends upon the ampere load squared times the resistance. The ampere capacity depends upon the voltage for which the motor is wound.

**Fig. 8. Performance curves for special differentially wound exciter**

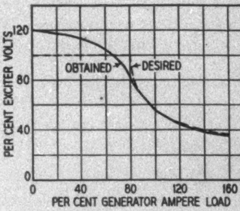
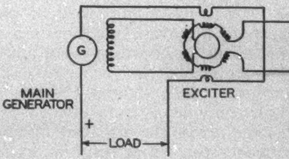


**Fig. 9. Connection diagram for special exciter to improve performance**



The motor used with the Diesel-electric equipment does not have to stand line surges. Also, all the field coils can be placed on one, preferably the negative, side of the line, and the motor can be operated on an ungrounded circuit or one with a midpoint grounded. The insulation requirements hence are not so severe as with conventional trolley operation, and this is conducive to higher specific output.

As previously stated, the voltage of the motor can be selected to give a most economical design of motor and generator combination. Freedom from line surges permits the use of higher commutating and flashing constants, which also tends toward lighter weight. The selection of a "natural" rather than an arbitrary voltage for the motor permits the use of more conservative designs as regards commutating characteristics. Multiple windings instead of 2 circuit windings are being used to a larger extent, and this permits the use of higher speeds with very conservative commutating and flashing characteristics, and motors of lighter weight.

The ampere ratings of the motors and generators should match very closely and hence, to obtain flexibility so that several motors can be used with the same generator, the following system is found to be useful:

| Generator | | | | Motor | | |
|---|---|---|---|---|---|---|
| Size | Kw | Volts | Amperes | Size | Volts | Amperes |
| A | 800 | 800 | 1,000 | A | 800 | 500 |
| B | 640 | 640 | 1,000 | B | 640 | 500 |
| C | 500 | 500 | 1,000 | C | 500 | 500 |
| D | 400 | 400 | 1,000 | D | 400 | 500 |
| E | 320 | 640 | 500 | E | 640 | 250 |
| F | 250 | 500 | 500 | F | 500 | 250 |
| G | 200 | 400 | 500 | G | 400 | 250 |

These values are used for illustration. With series-parallel control of the motors, the generator ampere capacity often can be from 10 to 15 per cent less than the combined ampere capacity of the motors. It may be seen that with this system any of several motors can be used with any one of several generators provided their limitations are not exceeded, and still match in current rating. For example, 2 B motors can be used with a B generator, and will give a speed range of 2.5 to 1; or, with the same generator, 4 B motors arranged 2 permanently in series will give a speed range of approximately 5 to 1; 4 C motors will give a speed range of 4 to 1, or 2 A motors will give a speed range of 3.2 to 1. Four E, F, or G motors could be used in parallel on B, C, or D generator. Various other combinations will be obvious.

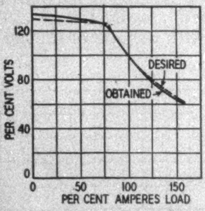


Fig. 10. Performance curves for generator with special exciter

As previously noted, field shunting of the motors is generally used. By shunting the motor field at the higher speed, the current demand from the generator at a given tractive effort and speed is increased and the maximum voltage is reduced. The use of field control, therefore, permits the use of a generator without excessive maximum voltage and hence a smaller size. With generator having 25 per cent overvoltage as indicated by the curve of figure 5, the motor will have a range, within its continuous capacity, of 1.5 to 1 in speed without any field control and using full engine power. By using one step of field control, this range can be increased to 2 to 1, with 2 steps the range can be increased to 3 to 1, and with 3 steps the range can be increased to $4^1/_2$ to 1. Also it may be noted that series-parallel control generally is used. Where a very wide range of tractive effort is needed, the use of series-parallel control of the motors will reduce the maximum demand on the generator. The maximum overload on the generator need not exceed 60 per cent even with 200 per cent or more overload on the motors.

The general tendency is to use antifriction roller bearings for the armature, and sleeve bearings of the constant-oil-level type for the motor axle bearings. Likewise, the tendency toward roller bearings for the main axle journals leads to a need for early agreement on new standard axles for this type of high speed equipment. In addition to standard axle sizes, there is a need for standard physical mounting dimensions to permit interchangeability of motors on a given truck. To secure long life of the motors with the minimum of attention, motors should be supplied with clean air free from road-bed dirt, sand, etc.

From the above, it may be seen that motors designed for Diesel-electric equipment do not have the same limitations as motors designed for trolley operation. As a result a distinctive line of motors has been and is being developed to meet the particular needs of this type of service. Standard types of railway motors such as are used on trolley type cars and locomotives can be and have been used, of course, but they are far from the most suitable from the standpoint of weight, performance, and cost.

Fig. 11. A typical main driving motor

## GENERATOR AND MAIN MOTOR COMBINED PERFORMANCE

The combined characteristics of generator and motors are given in figure 14. These curves are plotted in per cent.

The performance for a trolley operated, 1,500 volt, high speed, 2-car train for interurban and suburban service is indicated in figure 15. With this equipment on 1,350 volts average, the train can be accelerated to 34 miles per hour at 2.25 mphps in approximately 15 seconds, to 50 miles per hour in 25 seconds, and will reach a balancing speed of 95 miles per hour. With power supplied to the same motors from a 600 horsepower Diesel engine generator set (as also shown in figure 15) the balancing speed may be the same, but the maximum acceleration can be carried only up to 6.5 miles per hour. The voltage available for the maximum acceleration is 675 per motor when fed from trolley, but it is only 170 volts, or $^1/_4$ as much, when fed from the Diesel engine power plant. On a 2 per cent grade, 65 miles per hour can be attained with the trolley operated equipment, but only 45 miles per hour is attained with the Diesel electric equipment.

In figure 16 are shown typical performance data for a Diesel-electric car equipment with a 1,000 horsepower (net to generator) engine and 2 motors geared for a maximum operating speed of 100 miles per hour and continuous operating speed (utilizing full engine power) of from 40 to 80 miles per hour, and with overload tractive effort up to $3^1/_2$ times the continuous tractive effort. Combined data of figure 17 are typical for a locomotive equipment with the same power plant, but using 4 motors geared for a maximum speed of 63 miles per hour and continuous operating speed (utilizing full engine power) of from 12.5 to 50 miles per hour. The continuous tractive effort is 25,000 pounds and the overload tractive effort is more than ample to slip the wheels with axle loadings of from 50,000 to 63,000 pounds.

It should be noted here that the ratio between the maximum operating speed and the lowest continuous operating speed is $2^1/_2$ to 1 in the case of the car equipment, and 5 to 1 in the case of the locomotive equipment using twice as many motors. If the engine power on the locomotive is reduced 50 per cent to 500 hp, the speed ratio is increased further to approximately 10 to 1. With maximum single reduction gearing and modern high-speed motors, the lowest maximum speed usually is from 55 to 65 miles per hour; hence, where only low power is necessary with resultant low speed, the speed ratio becomes very high.

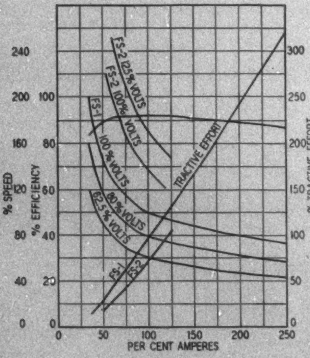


**Fig. 12. Typical motor performance curves**

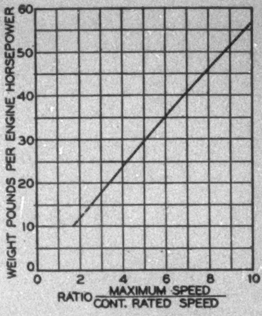


**Fig. 13. Motor weight as function of speed ratio**

In figure 13 the weight of the motor per engine horsepower is plotted as a function of the speed ratio. A simple rule is to take the weight of the motors to be proportional to the continuous tractive effort times the maximum safe speed, or

Weight = $K \times$ Cont. T. E. $\times$ Max. Speed

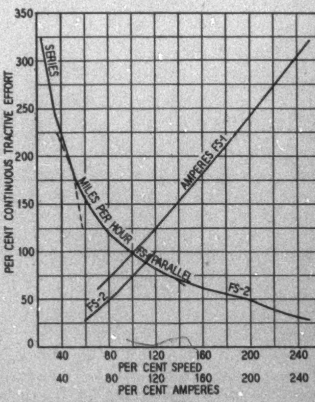


**Fig. 14. Combined motor- and -generator characteristics**

$K$ varies from 0.016 to 0.020. Where the maximum reduction gear ratios are used, the maximum safe speed does not vary greatly with the size of the motor. Hence, for separately ventilated motors used on locomotives with maximum reduction gears,

Weight = $K_2 \times$ Cont. T. E.

$K_2$ usually varies between 1 and 1.25, and is a function of the size and up-to-dateness or suitability of the design of the particular motor. The tractive effort is a function of the locomotive weight, and hence the motor size also is a function of the locomotive weight. Usually the motors amount to approximately 12 or 14 per cent of the locomotive weight. With the progress which has been made in motors designed for Diesel-electric locomotives, the tendency is to use a higher ratio of tractive effort per ton of locomotive weight rather than to reduce the proportion of the weight of the motor. Where the locomotive is operated in the most severe service, forced ventilation from a separate blower is used. With lighter service, the ventilation can be reduced, and in extremely light service the motors are sometimes operated enclosed.

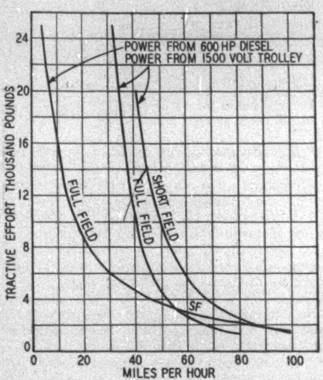


Fig. 15. Performance curves for typical 2-car Diesel - electric train

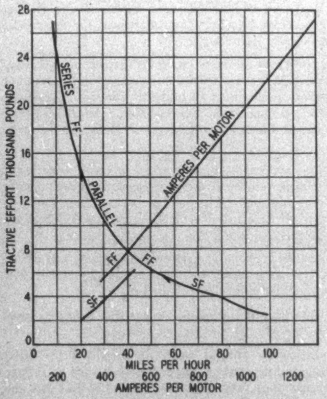


Fig. 16. Performance curves for 1,000 horsepower Diesel-electric car

## Auxiliary Operation

Where low voltage electrically operated auxiliaries such as air conditioning units, air brake compressors, radiator blower motors, main blower motors, locomotive and car lights, and battery charge are used, it may be desirable to supply them from the main generator while idling the engine. This can be arranged by using the shunt field separately excited from the battery and using the series starting field as a differential series field to limit the battery charging current and to regulate the voltage. When running at full engine speeds, auxiliary power is supplied from a separate auxiliary generator mounted on the commutator end of the main generator, or driven from the generator end by a coupling or belt. In some cases, the auxiliary generator is made large enough to carry the load at all engine speeds. This greatly increases its weight, but simplifies the control. Separate engine driven auxiliary generators also have been used.

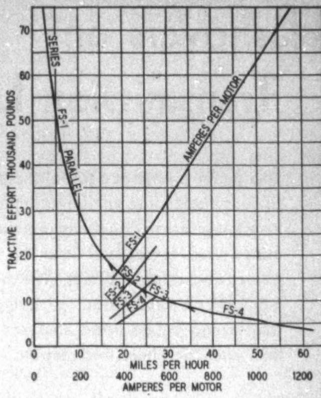


Fig. 17. Performance curves for 1,000 horsepower Diesel-electric locomotive

## Engine Starting

The most convenient means for starting the engine is to use the generator as a starting motor. With generator voltage around 600 and battery voltage of 64 volts, which is about 10 per cent of the generator voltage, it is necessary to use considerable care in keeping down the resistance of the starting circuit. Usually slightly more than full engine torque is necessary for break-away and about 30 per cent of engine torque usually is necessary for spinning the engine at the firing speed which is usually about a sixth of the running speed. A small, low resistance, series field can be provided for starting. This field must be proportioned to give sufficient break-away torque and also to enable the engine to be brought up to its firing speed.

From the foregoing, it may be seen that there has been considerable development in the design of generators and motors for Diesel-electric equipments. Furthermore, additional progress can be expected as the ultimate design by no means has yet been reached. The tendency will be toward lighter weight per engine horsepower, toward equipments of greater horsepower, and toward greater efficiency.

# Flashovers on Transmission Lines

**This paper is intended to be of practical use to transmission line engineers in that it shows how transmission line flashovers may be estimated and segregated into 1, 2, and 3 phase, and double circuit, flashovers. The method of calculation is comparatively simple and based upon analyses of statistical and analytical information.**

By
**L. V. BEWLEY**
ASSOCIATE A.I.E.E.

General Electric Co.,
Pittsfield, Mass.

MUCH has been written concerning the proper design of the protective features for overhead transmission lines required to secure immunity from flashovers caused by lightning. But more generally, the operating engineer is interested in knowing the comparative protective levels of his existing lines, and what improvement can be realized by relatively inexpensive changes, such as a reduction in tower footing resistances, additional insulator disks, or differential insulation on double circuit lines. The ideal is to be sought, but it is not always economically justifiable. Therefore it is the object of this paper to discuss line flashovers in general, and to present curves, data and procedures which will enable the operating engineer to estimate with engineering accuracy the lightning characteristics of his line. These estimates, however, will be no better than the accumulated statistical data upon which they are partially based.

## RÉSUMÉ AND CONCLUSIONS

1. Comparatively simple calculations, in conjunction with a curve of lightning severity, make possible the estimation of the percentage of flashovers on a transmission line, and to segregate this percentage into 1, 2, and 3 phase flashovers; also into single or double circuit flashovers. These estimates are possible for lines with or without ground wires, expulsion gaps, or differential insulation.

2. The factors entering into the estimate are:
*a.* surge impedance of the lightning stroke
*b.* self surge impedance of a conductor, including the effect of corona and ground current levels
*c.* mutual surge impedances
*d.* surge impedance of several conductors in parallel
*e.* coupling between conductors and groups of conductors
*f.* tower footing impedances
*g.* length of span between towers
*h.* ground wire clearance and conductor spacing
*i.* normal frequency voltage magnitude and polarity
*j.* impulse sparkover characteristics of insulators
*k.* statistical curve of lightning severity (current *versus* number exceeding)

3. In all cases, the lightning current necessary to cause flashover is given by an equation of the form:

$$I = \frac{(\text{impulse flashover voltage of insulator}) - (\text{polarity effect})}{(\text{equivalent resistance})(1 - \text{coupling factor})}$$

The "insulator impulse flashover voltage" depends upon number and type of insulators; and upon the surge duration as influenced by reflections from neighboring towers, hence upon the length of span.

The "polarity effect" depends upon the instantaneous normal frequency voltage and polarity of the stricken conductor and that of the next conductor to be involved. The voltage on the stricken conductor is modified by the surge impedance of the stroke. Polarity effect is instrumental in determining the next phase that will flash over, but is not a ruling factor in determining the total number of flashovers.

The "equivalent resistance" takes into account the tower footing resistance, surge impedance of the stroke, and surge impedances of any conductors involved. It is so defined that the calculated lightning current is the current which the stroke could deliver to a zero resistance ground, and this makes possible the correlation of all calculations on the basis of a single lightning severity curve.

The "coupling factor" depends upon the self and mutual surge impedances and the number of conductors involved. It is the dominating factor in limiting a flashover to a single phase, for the coupling greatly increases when one phase flashes over, thus mitigating the chance of other phases flashing over.

4. There is even yet insufficient appreciation that a reduction of tower footing resistance is a very effective method of reducing flashovers as compared with the addition of insulation. A line with 9 insulator units and 15 ohms tower footing resistance is more immune to lightning than a line with 20 insulator units and 35 ohms footing resistance.

5. A line of 9 insulator units equipped with a ground wire of proper midspan clearance and perfect shielding and having tower footing resistances not greater than 15 ohms should, except for occasional freak strokes, be practically lightning proof.

6. Complete immunity from midspan flashovers requires a midspan ground wire clearance of 35 feet on 1,000 foot spans; yet the number of flashovers for a midspan clearance of half this value is only about 5 per cent of the total strokes contacting the line. Therefore, high ground wire clearances probably cannot be justified except for very important lines.

7. Two ground wires are superior to a single ground wire for 3 reasons: (a) the shielding is more effective in preventing a lightning stroke from directly contacting a line conductor, (b) the surge impedance of 2 ground wires in parallel is $^{1}/_{3}$ less, and (c) the coupling with the line conductors is $^{2}/_{3}$ more.

8. Expulsion gaps cannot prevent all midspan flashovers, but otherwise may be as effective as ground wires. At intervals of 500 feet or less, they give practically complete protection.

9. Wooden cross arms may materially increase the lightning level of a line.

10. Excessive insulation to ground, such as provided by wood poles and insulating gaps, not only is an ineffective way to reduce outages on high voltage lines (say above 66 kilovolts) but has the decided disadvantage of compelling most of the flashovers to involve 2 or 3 phases (mostly the latter). (On lines of lower voltage, where induced strokes are important, wood should prove very beneficial.) Moreover, on such lines the number and severity of the surges reaching the station are far greater than would be the case with grounded hardware, or with expulsion gaps on the line.

11. Grounded hardware on high voltage wood pole lines increases the number of single phase flashovers, but greatly reduces the number of 2 or 3 phase flashovers. This is a marked advantage in those cases where single phase faults can be tolerated but phase-to-phase faults cannot. Also, grounding the hardware may prevent some pole splitting.

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12. On double circuit towers, most of the multiple phase flashovers will involve both circuits.

13. On double circuit lines equipped with adequate ground wires and having sufficiently low tower footing resistance the flashovers can, by an insulation differential equivalent to 2 times the normal frequency crest voltage, be restricted to one of the circuits. This differential can be secured either by changing the number of insulator units in the strings, or by equipping one of the circuits with expulsion gaps. In the latter case the flashovers do not result in outages.

14. The method of calculation developed in this paper is not limited to the types of structures illustrated, but may be applied quite generally to evaluate the comparative protective levels of different arrangements.

## CLASSIFICATION OF LIGHTNING STROKES

Whether or not a transmission line will flash over when struck by lightning depends upon the magnitude and characteristics of the lightning, and the characteristics of the protective equipment of the line. For the purpose of this paper the lightning surge itself is sufficiently characterized by 3 factors:

1. Current (or voltage) of the stroke.
2. Wave front of the lightning impulse.
3. Surge impedance of the stroke.

Of these, the current is most definitely known. Hundreds of records obtained with magnetic links on towers have been published in both the United States[1] and Germany.[2] Lewis and Foust[1] have classified these records as shown in figure 1 for lines having a protective level greater than 5,000 tower-footing amperes. When lightning currents necessary to cause a flashover are calculated in this paper, it will be understood that these currents are the ones which would flow if the ground resistance were zero, rather than the current actually delivered by the stroke if the ground resistance is other than zero. This is a necessary correlation, because 2 identical strokes may deliver quite different currents, depending upon the impedances which they encounter.

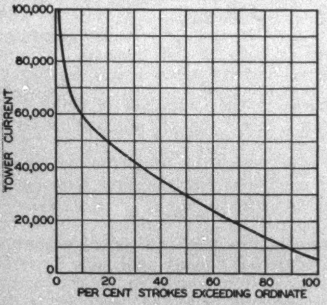

**Fig. 1. Lightning severity classification (Lewis and Foust)**

Lewis and Foust[1] also have classified the wave fronts and wave lengths of traveling waves resulting from natural lightning as measured from cathode ray oscillograms, and have found that the great majority of these traveling waves have fronts several microseconds long. However, since all except one of their oscillograms were taken at points on the line remote from the point where the lightning struck the line, it is likely that the wave fronts had been considerably flattened by distortion, and therefore that the initial fronts were steeper. For this reason it will be assumed that the lightning impulse initially may have a front as short as one microsecond.

The surge impedance of a lightning stroke has been variously estimated at from 200[3] to 400 ohms,[4] but no actual measurements have been possible. The latter value will be used throughout this paper. If it is in fact lower than 400 ohms, the comparative results given hereafter will have to be altered somewhat. More definite information about the surge impedance of a lightning stroke is at present the principal requirement in the study of transmission line protection; and until this factor is settled, all lightning calculations must, to a certain extent, be relative rather than absolute.

## LINE PARAMETERS

When lightning contacts a ground wire or line conductor, traveling waves appear not only on the stricken wire, but also, by induction, on all neighboring wires. The main wave appearing on the stricken wire depends upon the traveling wave $e_0$ coming down the lightning stroke, the surge impedance $Z_0$ of the stroke, the self-surge impedance $Z$ of the stricken wire, and any other impedance $R$ connected at the point of contact. The wave induced on adjacent wires (of the same sign as the main wave) depends, in addition, upon the mutual-surge impedance $Z'$ between wires. The self-surge impedance of an overhead conductor is roughly equal to 500 ohms if there is no corona, but if the voltage is high, corona greatly reduces this value, and at the very high potentials which may develop at midspan due to a stroke there, the surge impedance may be as low as 300 ohms. However, a high resistance earth causes the ground current to flow at greater depths and this increases the surge impedance. Actually, both corona and a resistive earth give rise to multivelocity waves,[5] hence the concept of a single self-surge impedance for each wire is not entirely tenable. Nevertheless, over the short time intervals with which this paper is concerned, the multivelocity waves will not have had time to separate, and an average self-surge impedance may be used.

The mutual surge impedances will average between 100 and 150 ohms, and therefore the coupling factors will be of the order of 0.25, 0.40, 0.50, and 0.57 respectively for 1, 2, 3, or 4 conductors in parallel.

Detailed formulas for the self and mutual surge impedances and the coupling factors are given in appendix I.

McEachron[9] has shown experimentally that the impulse voltage necessary to cause flashover of a string of insulators is changed by an amount approximately equal to the instantaneous value of the 60 cycle voltage across the insulators. The evaluation of this normal frequency polarity effect in the case of transmission lines is carried out in appendix II, where it is shown to depend upon the surge impedances and the number of line conductors involved.

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[1] For all numbered references, see list at end of paper.

## LIGHTNING STROKES TO A TRANSMISSION LINE

Lightning may contact a ground wire, tower, line conductor, or some combination of these. The resulting impulse voltages will be different in the different cases, but, as shown in appendix III, in all cases the lightning current necessary to cause an insulator flashover is given by

$$I = \frac{(V - e)}{R'(1 - F_n)}$$

where

$V$ = impulse voltage necessary to flash over the insulator
$e$ = normal frequency polarity effect
$R'$ = equivalent resistance
$F_n$ = coupling factor, depending upon the number $n$ of conductors involved.

On the assumption of a negative lightning stroke, the insulator impulse voltage $V$ is to be taken with *negative* sign, while the normal frequency voltage $e$ is to be taken with its appropriate instantaneous value as defined in appendix II. There are, then, the following possibilities:

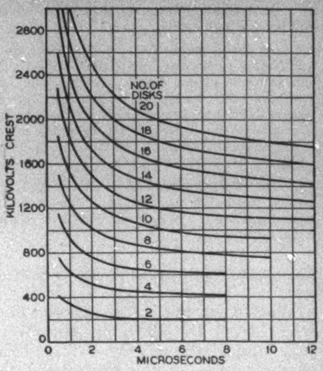
| | | Surge Imp. | Coupling Factor | Equivalent Resistance | Normal Frequency Effect |
|---|---|---|---|---|---|
| Stroke to | Flashover to | Eq. (6) $Z_n$ | Eq. (7) $F_n$ | Eq. (17) or (18) $R'$ | Eq. (9) or (11) $e$ |
| No. 1 line wire | No. 2 line wire | 500 | 0.25 | $\frac{1}{1/Z_0 + 2/Z_1} \cong 154$ | $\frac{e_1}{2} - e_1$ |
| No. 1 and No. 2 line wires | No. 3 line wire | 315 | 0.40 | $\frac{1}{1/Z_0 + 2/Z_2} \cong 113$ | $\frac{-4}{3} e_1$ |
| Tower (no. ground wires) | No. 1 line wire | — | 0.00 | $\frac{1}{1/Z_0 + 1/R}$ | $-e_1$ |
| Tower (1 ground wire) | No. 1 line wire | 500 | 0.25 | $\frac{1}{1/Z_0 + 2/Z_1 + 1/R}$ | $-e_1$ |
| Tower (2 ground wires) | No. 1 line wire | 315 | 0.40 | $\frac{1}{1/Z_0 + 2/Z_2 + 1/R}$ | $-e_1$ |
| No. 1 line wire | Tower | 500 | 0.00 | $\frac{1}{1/Z_0 + 2/Z_1}$ | $\frac{e_1}{2}$ |

If there are no ground wires, the insulator flashover voltage $V$ is taken (with negative sign for a negative lightning stroke) from the characteristic curves (figure 2) for the minimum voltage which can cause flashover.

But if there are ground wires, reflections return to the stricken point from neighboring towers, thereby reducing the effective duration of the surge and therefore increasing the voltage necessary to cause flashover. Hence the impulse flashover voltage $V$ is a function of the length of span and the tower footing resistance. It happens, however, that for a ground wire to prove at all effective, the tower footing resistance must be small compared with the surge impedance. For this reason, the wave shape at the stricken tower is essentially a function only of the span lengths. This wave shape can be computed[7] and the corresponding insulator flashover voltage estimated. In the upper part of figure 5 these insulator flashover characteristics are given for different lengths of span.

The radial straight lines in the lower half of figure 5 give the net *kilovolts across the insulator* as functions of the lightning current for different *effective resistances*. This effective resistance is defined as

**Fig. 2. Tentative data relating to insulator flashover characteristics, based upon standard 10 inch disks spaced 5$^3/_4$ inches apart**



$$R' = \frac{1}{(1/R + 1/Z_0 + 2/Z)}$$

hence in ordinary cases where the tower footing resistance $R$ is small compared with the surge impedance $Z_0$ (= 400 ohms) and $Z$ (= from 200 to 500 ohms) the effective resistance $R'$ is practically the same as the actual tower footing resistance $R$. Thus the dashed lines of figure 5 are simply curves of

$$R'I = (V - e)$$

while the full lines inelude 30 per cent coupling and are

$$(1 - F)R'I = (V - e)$$

The single curve in the lower half of figure 5 is the same as figure 1 except that the abscissa has been relabeled "per cent flashovers."

In ordinary cases where the tower footing resistance $R$ is small compared with the surge impedance of the line, it is sufficient to take $R' = R$ when estimating the flashovers due to a stroke to a tower or to a ground wire in the neighborhood of a tower. It is clear that figure 5 is equally applicable for estimating the flashovers from a stricken line conductor to an adjacent conductor or to the tower, using $R' = 113$ and $R' = 154$, respectively.

Thus figure 5 permits the calculation of the percentage of flashovers for all strokes occurring at or near the tower and for lines equipped either with or without ground wires. Three examples will make this clear.

*Example I.*—Given a 132 kilovolt steel tower line having 9 insulator units, 37 ohm tower footing resistances, 1,000 foot spans, and no ground wires; what size stroke can this line stand, and what per cent flashovers will be experienced?

A certain small percentage of the total strokes will strike the towers, but these will be ignored in comparison with the number of strokes striking a line conductor. But, for a stroke hitting a line conductor, the tower footing resistance does not influence the surge, and hence the *effective resistance* is

$$R' = \frac{1}{1/Z_0 + 2/Z} = \frac{1}{1/400 + 2/500} = 154 \text{ ohms}$$

The length of span is of no consequence, inasmuch as the resulting surge will not be altered by reflections from the towers until *after* flashover. Nor need the possibility of midspan flashovers be considered for, regardless of where the stroke hits the conductor, the voltage from the stricken conductor to the tower will exceed the voltage between conductors at midspan, because the coupling between conductors reduces the voltage between them. Hence, if flashover does not occur at the tower, it will not occur at midspan. If an exceedingly rapid rate of voltage rise causes a midspan flashover before the wave reaches the tower, it is a certainty that flashover also will follow at the tower. Therefore, a calculation of insulator flashovers at the tower includes all flashovers on the line. In estimating the minimum lightning currents which can cause flashovers, full wave flashover values on the 1.5x40 wave are used, such wave being regarded as a typical lightning wave. Normal frequency voltage on the line can be disregarded in this case, since the stricken conductor is just as likely to be positive as negative.

Therefore, in the upper part of figure 5 at 9 insulator units, and on the 1.5x40 curve, read 850 kilovolts across insulators. Entering the lower part of figure 5 at this value of 850, follow down vertically to the intersection with the dashed line 154 ohms, thence horizontally to intersection with the solid lightning current curve, where the coordinates will be found to indicate a tower current of 6,000 amperes (left hand scale), and 98 per cent flashovers (lower scale). Even increasing the line insulation to 12 units would reduce the flashovers only to 95 per cent. This makes it clear that such a line is practically defenseless against a direct stroke.

*Example II.*—Same line as in example I, except wood poles. The insulator flashover voltage of the 2 insulator strings and wood cross arm in series is equivalent to 20 insulator units.* Entering figure 5 at 20 on the upper left hand scale and following to the right to the 1.5x40 curve, it is seen that the flashover voltage is 1,750 kilovolts. This case differs further from that of example I in that flashover is now to another conductor instead of to a tower. Therefore, coupling is involved and the solid lines in the lower half of figure 5 must be used. Then, dropping vertically at 1,750 kilovolts to intersection with the 154 ohm solid curve, and following thence horizontally to the intersection with the lightning current curve, 17,300 amperes and 75 per cent flashovers are indicated. Later on it will be shown that these flashovers are practically all 3-phase flashovers. Wood pole construction usually results in phase-to-phase flashovers, while the flashovers to ground will concentrate at points of reduced insulation to ground, such as guyed poles. Furthermore, such construction greatly increases flashovers at the stations,[11] unless adequate lightning arresters are installed there. And finally, the surges of higher voltage may cause split poles. Incidentally, no station protective device can influence line flashovers[12] occurring an appreciable distance out on the line.

*Example III.*—Same line as in example I, except with a ground wire having adequate midspan clearance and correctly placed to give proper shielding.[15] In this case reflections return from neighboring towers and reduce the potential at the stricken tower, so that regardless of the duration of the lightning discharge, the surge at the stricken tower is shortened materially. This effect is introduced by using the curve in the upper part of figure 5 with the appropriate "length of span," in this case 1,000 feet. The effective resistance is now

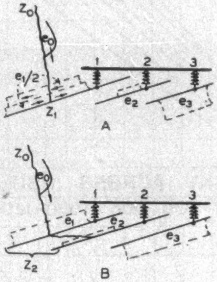


**Fig. 3. Lightning stroke contacting line conductors**

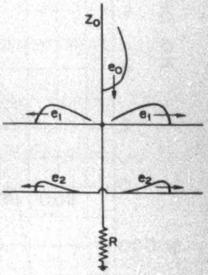


**Fig. 4. Lightning stroke contacting ground wire at tower**

$$R' = \frac{1}{1/37 + 1/40 + 2/500} = 30 \text{ ohms}$$

The "route" is indicated by a dashed line with arrows on figure 5 for this example, and it may be seen that the line can withstand a stroke of 50,000 amperes at or near the tower, and that 18 per cent of all strokes will cause an insulator flashover. In this calculation the normal frequency polarity has been ignored. It may be accounted for in either of 2 ways: (1) Find the *kilovolts across insulators* in the upper part of the chart in the usual way and then, before entering the lower part of the chart, deduct from this value the normal frequency line-to-neutral crest voltage, or, (2) deduct from the actual *number of insulators* the number corresponding to the normal frequency as given in the following table:

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| System Kv.......... | 50 | 69 | 92 | 115 | 138 | 161 | 196 | 230 | 287 |
| 60 Cycle Crest....... | 41 | 57 | 75 | 94 | 113 | 132 | 160 | 188 | 235 |
| Equiv. Insulators..... | 0.3 | 0.5 | 0.6 | 0.8 | 1.0 | 1.2 | 1.4 | 1.8 | 2.3 |

---

* Very little allowance has been made in this example for the wood cross arms, as limited laboratory tests indicate that the wood may add very little to the over-all strength until it equals in strength the flashover voltage of the insulator string itself. It does not appear permissible to add the flashover voltage of the wood directly to that of the insulators. Furthermore, wood itself is quite variable, and may have a flashover voltage anywhere from very low values to 300 kilovolts per foot. Nevertheless, in those cases where confidence is felt in the wood cross arms, the methods of this paper can be used for estimating flashover, either by using the over-all flashover voltages in the equations, or by expressing the wood in terms of an equivalent number of insulators.

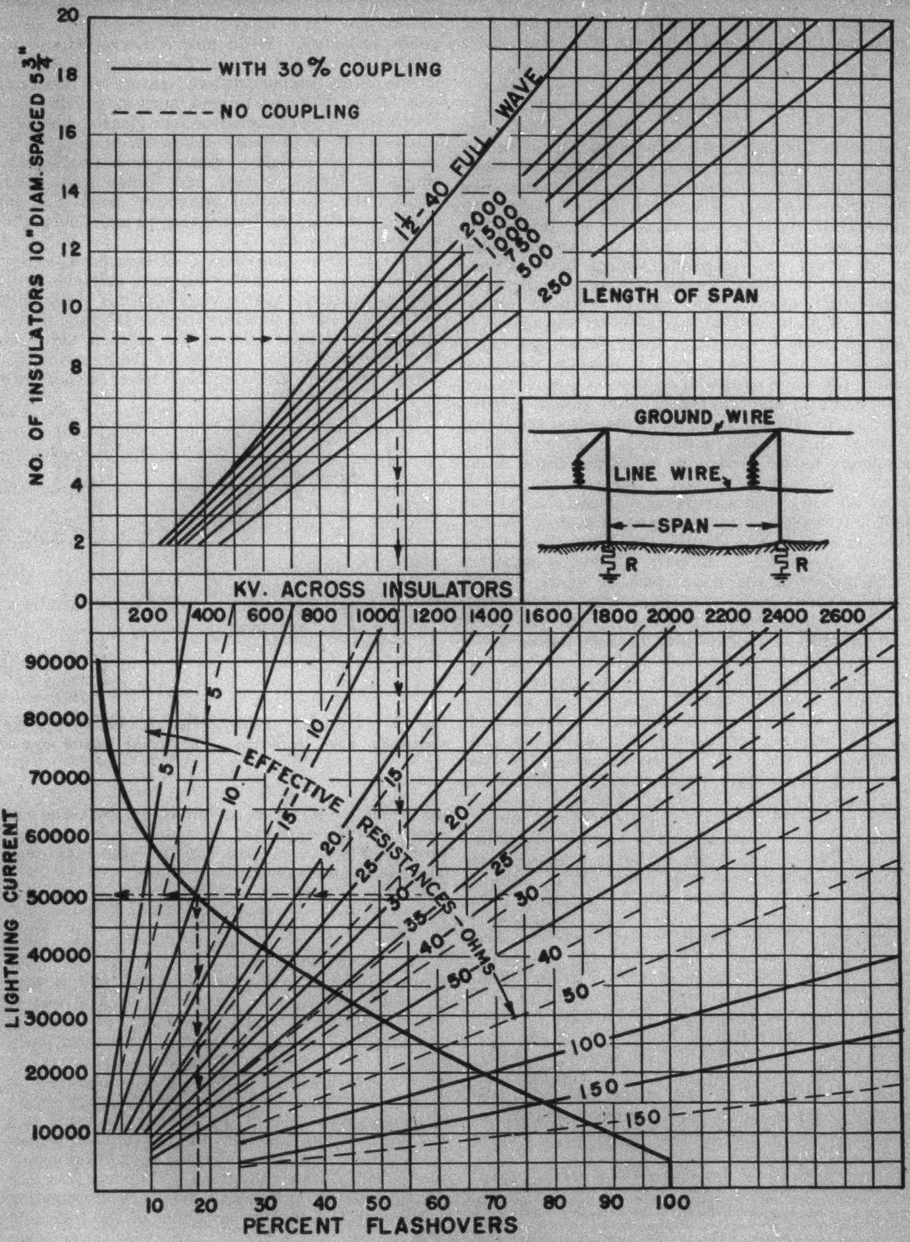


Fig. 5. Charts for calculation of flashover expectancy

For ordinary purposes it is hardly worth-while to include this refinement. The net effect will be shown later in connection with figure 8.

Suppose it is required to reduce to 10 per cent instead of 18 per cent the flashovers caused by strokes to the tower or to the ground wire at or near the tower. From figure 5 it may be seen that this can be accomplished either by increasing the insulator strings to 11 units, or by reducing the effective tower footing resistance to 25 ohms. It is apparent that increasing the insulation is a much less effective way of reducing flashovers than by decreasing tower footing resistance. Indeed, a line with 9 insulator units and 15 ohms tower footing resistance is more immune from lightning flashover than a line with 20 insulator units and 35 ohms footing resistance! The great desirability of keeping the tower footing resistances down cannot be too highly emphasized.[3] The data accumulated to date indicate that in those localities where ground footing resistances less than 10 or 15 ohms can be obtained a line of 9 or 10 insulator units, equipped with a proper ground wire, should be nearly immune to lightning, and there is little excuse, as far as lightning is concerned, in going to higher insulation.

In the above analysis, it was assumed that the ground wire adequately shielded the line conductors; that is, no stroke was permitted to contact a line conductor directly. Actually, a few strokes may evade the ground wire and strike a line conductor. There is at present no way of estimating the number of these. Such strokes are ignored in this analysis.

In the present example it was postulated that the ground wire midspan clearance should be adequate to prevent midspan flashover. Nevertheless, it is necessary to consider the possibility of a midspan stroke causing an insulator flashover at adjacent towers. Of course, the successive reflections can be calculated and the voltage at the towers determined.[7] Such calculations show that the tower top voltage for a stroke to the ground wire at midspan is approximately half that for a stroke of equal severity at the tower. Thus, if the tower footing resistance is low enough for the insulators to stand a 50,000 ampere stroke at the tower, there will be no danger for currents of approximately double this value at midspan.

The question now arises: what of those strokes which are neither at the tower nor at midspan? This question cannot be disposed of rigorously, but from a study of the resulting wave shapes for lightning strokes to arbitrary points on the line, it appears reasonable at least for estimating purposes to assume that:

> Any stroke within a quarterspan of a tower will be considered equivalent to a stroke to the tower itself, while any stroke within a quarterspan of midspan will be considered equivalent to a stroke to midspan.

Granting that a specific stroke elsewhere may exhibit characteristics quite different from those it would have if it occurred exactly at the tower or exactly at midspan, on the average the criterion as stated is believed to be as good as any. Therefore, in the foregoing example, where a ground wire with perfect shielding and adequate midspan clearance is assumed, only 18 per cent of the strokes within a quarterspan of the towers cause flashovers, and none of those within a quarterspan of midspan. Therefore, of *all* strokes hitting this line, only 9 per cent cause flashovers.

This typical example clearly illustrates the great advantage of a ground wire, provided the tower footing resistances are reasonably low and the midspan clearance is adequate.

### LIGHTNING STROKE TO MIDSPAN

Referring to figure 6, a lightning stroke is shown making contact with a ground wire at midspan. The waves appearing on the ground wire and traveling to the towers are

$$e = \frac{ZZ_0}{2Z_0 + Z} I$$

When these waves reach the towers, reflections start back toward midspan, given by

$$e' = \frac{-Z}{2R + Z} e$$

and upon reaching midspan reduce the voltage there by

$$\frac{-4ZZ_0}{(2R + Z)(2Z_0 + Z)} e$$

From this equation it is clear that, for any value of the tower footing resistance $R$ low enough to prevent excessive insulator flashovers, the reflections completely nullify the midspan voltage, or even may reverse its polarity. Assuming complete nullification, 2 cases must be considered: (a) When the wave front $F$ is greater than the length of span $T$, and (b) when it is less. These 2 cases are illustrated in figure 6. In the first case, $F > T$, it may be seen that the reflections arrive at midspan before the initial wave there has reached its crest, and consequently the net voltage at midspan and the duration of this midspan voltage are:

$$\left(\frac{T}{F}\right) e \text{ for a time} \qquad t = \left(F + \frac{T}{2}\right)$$

However, if $F < T$, the midspan voltage is

$$e \text{ for a time} \qquad t = \left(T + \frac{F}{2}\right)$$

The voltage between the stricken ground wire and the line conductor is

$$e_s = (1 - F) \qquad e = (1 - F)\left(\frac{ZZ_0}{Z + 2Z_0}\right)\alpha I$$

where

$$\alpha = \frac{T}{F} \text{ and } t = (F + T/2) \text{ if } F > T$$

$$\alpha = 1 \text{ and } t = (T + F/2) \text{ if } F < T$$

In applying the above equation, the surge impedance $Z$ of the ground wire, as well as the coupling factor, should include the effects of corona; for under the condition of a midspan strike the voltage on the ground wire may be several million volts, say from 3,000 to 15,000 kilovolts. To take this into account properly a cut-and-try solution is necessary. This can be avoided, without entailing much error, by using the corona corresponding to about 5,000 kilovolts. This has been done in the $\alpha I$ curves of figure 7, the solid-line curves applying to line conductor heights of 100 feet above ground and the dashed-line curves applying to line conductor heights of 50 feet above ground. To make some allowance for the depression of the current images in the ground, it is suggested that the $h = 100$ curves be used in all cases. There have been plotted also in figure 7 a sheath of lines representing impulse flashover voltages $e_s$ for various spacings $s$ between conductors and different time lags $t$.

In the inset of figure 7 the curve of figure 1 has been redrawn, and cutting it is a sheath of $\alpha$ lines relating current $I$ to $\alpha I$.

The use of figure 7 is as follows: (a) Compute the factor $\alpha$ and time lag $t$. (b) For a given midspan ground wire clearance $s$ find the vertical intersection with the appropriate $t$ curve, and interpolate the value of $\alpha I$. (c) For the value of $\alpha I$ and the calculated $\alpha$ find the lightning current $I$ from the inset curves and hence the per cent lightning flashovers. The above process, can be reversed, of course, to determine the proper midspan clearance to prevent the flashovers exceeding a specified number.

*Example.*—A line has spans of 750 feet and midspan ground wire clearance of 15 feet. What percentage of midspan flashovers can be expected? Assuming a lightning wave front not greater than 1 microsecond: there is $T = 0.75$; $F = 1.00$; $\alpha = 0.75$; $t = 1.375$; $s = 15$; and $\alpha I = 54{,}000$ (from figure 7).

The inset curves of figure 7 then give $I = 72{,}000$ amperes and 4 per cent flashovers. Since, on the average, only half the total strokes hitting the line will strike within a quarterspan of midspan, it follows that only 2 per cent of all strokes to the line will cause a line flashover out on the span.

If greater accuracy is desired than is afforded by the inset curves of figure 7, it can be obtained by dividing $\alpha I$ by $\alpha$ to find $I$ and consulting figure 1 for the per cent flashovers; but, in view of the assumptions involved, this refinement hardly seems justifiable.

Suppose, now, that it is required to increase the midspan ground wire clearance enough to prevent all flashovers on the span for lightning currents up to, say, 100,000 amperes. Then

$$\alpha I = 0.75 \times 100{,}000 = 75{,}000$$

In figure 7 this $\alpha I$ curve intersects the $t = 1.375$ curve at a midspan clearance of $s = 24$ feet.

These results are most enlightening. In the past, midspan ground wire clearances of from 30 to 35 feet on 1,000 foot spans have been advocated to prevent midspan flashovers.[13,14,15] Yet actual lines with ground wire clearances much less than this were known to operate without undue trouble from midspan flashovers. From the foregoing example it is clear that these good operating records are to be expected, because only a few per cent of the total strokes are capable of causing a midspan flashover, and yet, to prevent these few flashovers, normal ground wire clearances would have to be doubled.

## EXPULSION GAPS

The methods and curves of this paper may be used to estimate the number of operations of expulsion gaps and the effect of their distribution along the line.[16] For example, how many outages per 100 direct strokes to a line will be experienced under the following conditions?

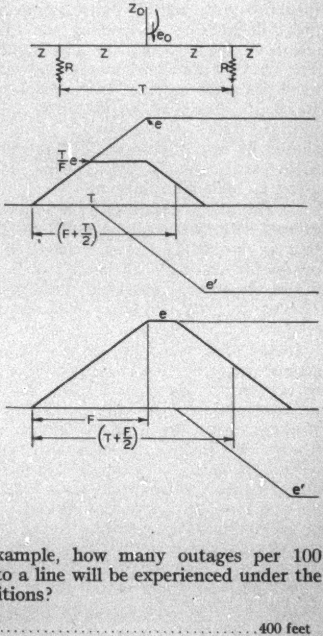


**Fig. 6. Effect of wave front and span length upon shape of surge at midspan**

| | |
|---|---|
| Length of spans | 400 feet |
| Spans between expulsion gaps | 4 |
| Insulators | 8 |
| Ground resistance at gapped towers | 100 ohms |

For a stroke at a gapped structure, the gaps on all 3 phases will operate for any surge sufficient to cause distress to an adjacent unprotected structure. Hence the effective resistance is

$$R' = \frac{1}{1/R + 1/Z_0 + 2/Z_s} = \frac{1}{1/100 + 1/400 + 2/250} = 49$$

The distance from the adjacent unprotected tower to the next expulsion gap is 1,200 feet, which is the "equivalent span." Then, consulting figure 5, it may be seen that the outages are 70 per cent.

For a stroke to a line conductor near the unprotected structure midway between gaps, the effective resistance is 154 ohms and the equivalent span is now 800 feet. From figure 5 the outages are shown as 97 per cent.

Now assuming that any stroke within a half-span of an expulsion gap is equivalent to a stroke at the gap itself while any stroke further away from a gap is equivalent to a stroke at an unprotected pole midway between expulsion gaps, it follows that the total flashovers will be

$$\frac{p_1 + (n-1)p_2}{n} = \frac{70 + 3 \times 97}{4} = 90 \text{ per cent}$$

in which

$n$ = spans between expulsion gaps
$p_1$ = per cent flashovers for a stroke at a gap
$p_2$ = per cent flashovers for a stroke midway between gaps

Thus, expulsion gaps at several span intervals are not very effective in reducing the outages. But, if gaps are installed on *every* pole, they provide good immunity from outages due to lightning.

Of course, expulsion gaps cannot prevent all midspan flashovers caused by strokes there. In the event of a stroke to one conductor at or near midspan, the stricken conductor may be regarded as a quasi-ground wire, and figure 7 used to compute the midspan flashovers. Thus on a 1,000 foot span and with 12 feet between conductors, the midspan flashovers, by figure 7, are 26 per cent of all strokes within a quarterspan of midspan, or 13 per cent of all strokes to the line.

## Comparison of Different Arrangements

For the purpose of comparing lines with different insulation and circuit arrangements, with and without ground wires, figure 8 has been prepared. These data pertain to a 132 kilovolt line having a normal insulation of 9 standard disks 10 inches in diameter and spaced $5^3/_4$ inches apart in the string, 750 foot spans, 15 foot midspan ground wire clearance, and 30 ohms tower footing resistances. The effect of coupling, self and mutual surge impedances, successive reflections between towers, magnitude and polarity of normal line voltage, and point of contact of lightning with the line, all have been taken into account in accordance with the considerations previously given in this paper. The relative number of 1, 2, and 3 phase flashovers have been evaluated and, in the case of double circuit lines, the flashovers on both circuits have been determined. The reader should find little difficulty in making a similar study of his own particular system; although some of the salient conclusions to be drawn from this typical example are so definite (and surprising) as to need no further elucidation. It may be remarked that 30 ohms tower footing resistance is rather low for a line without ground wires, where no particular effort is made to reduce it, and therefore the number of 3 phase flashovers here calculated is a lower proportion of the total than probably would be experienced on lines without ground wires.

In these calculations a self surge impedance of 500 ohms, and an average mutual surge impedance of 125 ohms have been used. It is hardly worthwhile to go to greater refinements, although there is nothing to hinder it if the calculator so desires.

*I. Wood Pole Line Without Ground Wire.*—Lightning of negative polarity is assumed to strike phase $A$, and, assuming flashover to take place along the wood crossarm, the first flashover will be to whichever other phase has the greatest normal frequency positive voltage, or, if the other 2 phases are alike in this respect, flashover is to that phase having the least coupling—in this case phase $B$ is shown further away from phase $A$ than from phase $C$, hence $B$ will have slightly less coupling. The surge impedance of the stricken conductor $A$ is taken as 500 ohms, and therefore the *equivalent resistance* is 154 ohms. The coupling between $A$ and $B$ is 125/500 = 0.25. The initial flashover involves insulators $A$ and $B$ and the wood cross arms in series. Since there will be no reflections from adjacent poles, the insulator flashover is taken on the 1.5x40 wave and for 2 insulators in series (neglecting the wood), there is 1,700 kilovolts. The net surge voltage to flash over the insulators (when $B$ is 108 kilovolts positive) is

$$V - \frac{e_1}{2} + e_2 = -1{,}700 - \frac{108}{2} + (-54) = -1{,}700 - 108 = -1{,}808$$

and hence the lightning current necessary to cause a flashover is

$$I = \frac{-1{,}808}{154 \times (1 - 0.25)} = -15{,}650 \text{ amperes}$$

which corresponds in figure 1 to 77 per cent flashovers. (Had the wooden crossarm been taken as equivalent to 1,000 kilovolts it would have required 24,000 amperes to cause flashover, and only 60 per cent of the strokes could cause a flashover.)

The possibility of a subsequent flashover from $A$ and $B$ in parallel to $C$ must next be considered. The surge impedance of 2 conductors in parallel is (500 + 125)/2 = 312; the coupling factor is now 125/312 = 0.40, and the effective resistance is

$$R' = \frac{1}{1/Z_0 + 2/Z_2} = \frac{1}{1/400 + 2/312} = 113$$

The net surge voltage to flash over insulator $C$ is

$$V + \frac{4}{3} e_2 = -850 + \frac{4}{3}(-54) = -850 - 72 = -922$$

and hence the lightning current to cause flashover of $C$ (*provided* $A$ and $B$ have already flashed over) is:

$$I = \frac{-922}{113(1 - 0.40)} = -13{,}500$$

which corresponds in figure 1 to 82 per cent flashovers; but, since only 77 per cent of the total strokes could have flashed over $A$ and $B$ previously, it follows that only 77 per cent of the flashovers actually can involve $C$.

That a stroke to a line conductor out on the span will precipitate an insulator flashover at the nearest structure already has been pointed out, therefore midspan flashovers need not be considered separately in this case. Therefore, the *correlation factor* for strokes at or near midspan and for strokes at or near the pole is unity.

The calculation for $A$ at zero and $-108$ kilovolts are similarly carried out. It is clear that the principal effect of normal frequency voltage is in determining the insulators which flashover, but that it does not materially change the percentage of flashovers.

Thus it is seen that on wood pole lines without ground wires a large percentage of the total strokes cause phase-to-phase flashovers, and practically all of these involve all 3 phases. Furthermore, the surge is not relieved, but will either flash over the pole or travel on to the station where it may endanger apparatus.

*II. Steel Tower Line Without Ground Wires.*—In this case the initial flashover is from the stricken conductor $A$ to the tower of footing resistance $R = 30$ ohms. The *equivalent resistance* is 154 ohms prior to the flashover of $A$. There is no *coupling* between $A$ and the tower.

After $A$ has flashed to the tower, the equivalent resistance is 25 ohms, and there is a 0.25 coupling with the other conductors. The voltage of $B$ or $C$ is subtracted (with proper regard to its polarity) from the insulator flashover voltage of $-850$ kilovolt to find the net surge voltage necessary to cause flashover of the next phase. When 2 phases already have flashed over, the equivalent resistance becomes 24 ohms and the coupling with the remaining phase is 0.40.

It is evident, in this case of steel tower lines without ground wires, that practically all strokes will cause at least a phase-to-ground flashover. The

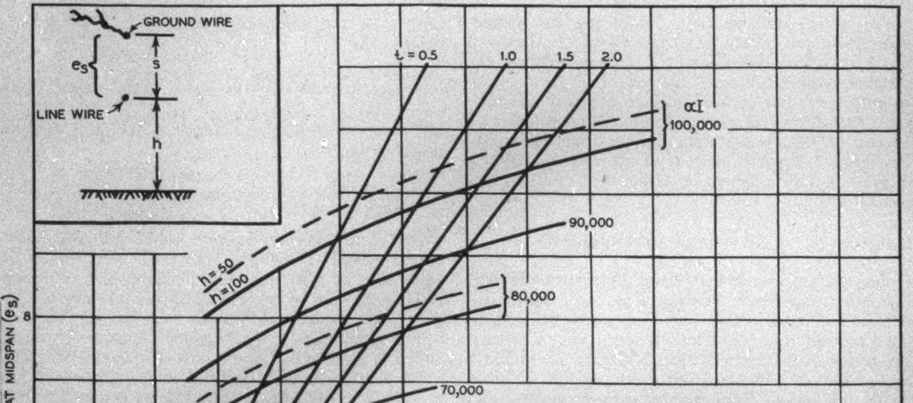


Fig. 7. Chart for calculating midspan flashovers

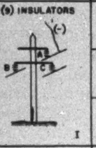
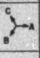
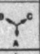
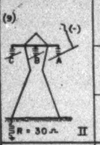
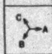
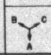
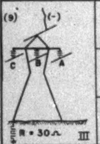
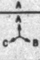
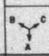
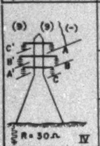
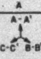
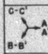
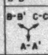
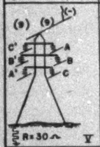
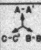
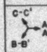
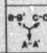
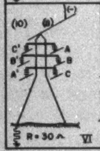
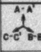
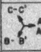
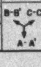
| 132 KV. SYSTEM | PHASE POLARITY | ORDER OF FLASHOVER | SYSTEM POTENTIAL | SURGE IMPEDANCE | EQUIVALENT RESISTANCE | COUPLING FACTOR | SURGE K.V. TO FLASHOVER INSULATORS | SURGE CURRENT | INSULATOR FLASHOVERS | MIDSPAN FLASHOVERS | CORRELATION FACTOR | TOTAL FLASHOVERS | TYPE OF FAULT | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | | | | | 1 ø | 2 ø | 3 ø | TWO CIRCUIT |
|  | | A<br>B<br>C | 108<br>-54<br>-54 | 500<br>315 | 154<br>113 | 0.25<br>0.40 | -1700-108=-1808<br>-850-72=-922 | 15650<br>13800 | 77<br>" | – | 1 | 77<br>" | 0 | 0 | 77 | |
| |  | A<br>C<br>B | 0<br>94<br>-94 | 500<br>315 | 154<br>113 | 0.25<br>0.40 | -1700+94=-1606<br>-850-125=-975 | 13900<br>14400 | 81<br>80 | – | 1 | 81<br>80 | 0 | 1 | 80 | |
| |  | A<br>B<br>C | -108<br>54<br>54 | 500<br>315 | 154<br>113 | 0.25<br>0.40 | -1700+108=-1592<br>-850+72=-778 | 13800<br>11500 | 81<br>" | – | 1 | 81<br>" | 0 | 0 | 81 | |
|  | | A<br>C<br>B | 108<br>-54<br>-54 | 500<br>500<br>315 | 154<br>25<br>24 | 0.00<br>0.25<br>0.40 | -850-54=-904<br>-850-54=-904<br>-850-54=-904 | 5900<br>48200<br>62800 | 98<br>20<br>8 | – | 1 | 98<br>20<br>8 | 78 | 12 | 8 | |
| |  | A<br>C<br>B | 0<br>94<br>-94 | 500<br>500<br>315 | 154<br>25<br>24 | 0.00<br>0.25<br>0.40 | -850-0=-850<br>-850+94=-756<br>-850-94=-944 | 5500<br>40300<br>71500 | 99<br>31<br>4 | – | 1 | 99<br>31<br>4 | 68 | 27 | 4 | |
| |  | A<br>C<br>B | -108<br>54<br>54 | 500<br>500<br>315 | 154<br>25<br>24 | 0.00<br>0.25<br>0.40 | -850+54=-796<br>-850+54=-796<br>-850+54=-796 | 6000<br>42500<br>56300 | 100<br>28<br>13 | – | 1 | 100<br>28<br>13 | 72 | 15 | 13 | |
|  |  | A<br>C<br>B | 108<br>-54<br>-54 | 500<br>315<br>250 | 25<br>24<br>23 | 0.25<br>0.40<br>0.50 | -1130+108=-1022<br>-1130-54=-1084<br>-1130-54=-1084 | 54600<br>82300<br>103000 | 14<br>2<br>0 | 5<br>1<br>0 | $\frac{1}{2}$ | 9.5<br>1.5<br>0 | 8 | 1.5 | 0 | |
| | | C<br>A<br>B | 94<br>0<br>-94 | 500<br>315<br>250 | 25<br>24<br>23 | 0.25<br>0.40<br>0.50 | -1130+94=-1036<br>-1130+0=-1130<br>-1130-94=-1224 | 58200<br>78500<br>106500 | 13<br>3<br>0 | 5<br>1<br>0 | $\frac{1}{2}$ | 9<br>2<br>0 | 7 | 2 | 0 | |
| |  | C<br>B<br>A | 54<br>54<br>-108 | 500<br>315<br>250 | 25<br>24<br>23 | 0.25<br>0.40<br>0.50 | -1130+54=-1076<br>-1130+54=-1076<br>-1130-108=-1238 | 57400<br>74700<br>107800 | 11<br>4<br>0 | 5<br>1<br>0 | $\frac{1}{2}$ | 8<br>2.5<br>0 | 5.5 | 2.5 | 0 | |
|  (9)<br>(9)<br>(-)<br>C'<br>B'<br>A'<br>A<br>B<br>C<br>R = 30 Ω<br>IV |  | A<br>A'<br>B'<br>C | 108<br>108<br>-54<br>-54 | 500<br>500<br>315<br>250 | 154<br>25<br>24<br>23 | 0.00<br>0.25<br>0.40<br>0.50 | -850-54=-904<br>-850+108=-742<br>-850-54=-904<br>-850-54=-904 | 5900<br>39600<br>62800<br>78700 | 98<br>33<br>8<br>3 | – | 1 | 98<br>33<br>8<br>3 | 90 | 5 | 3 | 33 |
| |  | A<br>C<br>C'<br>A' | 0<br>94<br>94<br>0 | 500<br>500<br>315<br>250 | 154<br>25<br>24<br>23 | 0.00<br>0.25<br>0.40<br>0.50 | -850-0=-850<br>-850+94=-756<br>-850+94=-756<br>-850-0=-850 | 5500<br>40300<br>52500<br>74000 | 99<br>31<br>15<br>4 | – | 1 | 99<br>31<br>15<br>4 | 68 | 31 | 0 | 15 |
| |  | A<br>C<br>C'<br>B' | -108<br>54<br>54<br>54 | 500<br>500<br>315<br>250 | 154<br>25<br>24<br>23 | 0.00<br>0.25<br>0.40<br>0.50 | -850+54=-796<br>-850+54=-796<br>-850+54=-796<br>-850+54=-796 | 5200<br>42400<br>55300<br>69200 | 100<br>28<br>13<br>5 | – | 1 | 100<br>28<br>13<br>5 | 71 | 23 | 5 | 13 |
|  (9)<br>(9)<br>(-)<br>C'<br>B'<br>A'<br>A<br>B<br>C<br>R = 30 Ω<br>V |  | A<br>A'<br>B<br>B' | 108<br>-54<br>-54<br>-54 | 500<br>315<br>250<br>219 | 25<br>24<br>23<br>22 | 0.25<br>0.40<br>0.50<br>0.57 | -1130+108=-1022<br>-1130-54=-1184<br>-1130-54=-1184<br>-1130-54=-1184 | 54600<br>82300<br>103000<br>125000 | 14<br>2<br>0<br>0 | 5<br>1<br>0<br>0 | $\frac{1}{2}$ | 9.5<br>1.5<br>0<br>0 | 9.5 | 0 | 0 | 1.5 |
| |  | C<br>C'<br>A<br>A' | 94<br>94<br>0<br>0 | 500<br>315<br>250<br>219 | 25<br>24<br>23<br>22 | 0.25<br>0.40<br>0.50<br>0.57 | -1130+94=-1036<br>-1130+94=-1036<br>-1130+0=-1130<br>-1130+0=-1130 | 55200<br>71900<br>98300<br>119800 | 13<br>4<br>1<br>0 | 5<br>1<br>0<br>0 | $\frac{1}{2}$ | 9<br>2.5<br>0<br>0 | 9 | 0 | 0 | 2.5 |
| |  | B<br>B'<br>C<br>C' | 54<br>54<br>54<br>54 | 500<br>315<br>250<br>219 | 25<br>24<br>23<br>22 | 0.25<br>0.40<br>0.50<br>0.57 | -1130+54=-1076<br>-1130+54=-1076<br>-1130+54=-1076<br>-1130+54=-1076 | 57300<br>74700<br>93500<br>113500 | 11<br>4<br>1<br>0 | 5<br>1<br>0<br>0 | $\frac{1}{2}$ | 8<br>2.5<br>0.5<br>0 | 8 | 0 | 0.5 | 2.5 |
|  (10)<br>(8)<br>(-)<br>C'<br>B'<br>A'<br>A<br>B<br>C<br>R = 30 Ω<br>VI |  | A<br>B<br>C<br>A' | 108<br>-54<br>-54<br>108 | 500<br>315<br>250<br>219 | 25<br>24<br>23<br>22 | 0.25<br>0.40<br>0.50<br>0.57 | -1020+108=-912<br>-1020-54=-1074<br>-1020-54=-1074<br>-1250+108=-1142 | 48700<br>74600<br>93600<br>120500 | 20<br>4<br>1<br>0 | 5<br>1<br>0<br>0 | $\frac{1}{2}$ | 12.5<br>2.5<br>0.5<br>0 | 10 | 2 | 0.5 | 0 |
| |  | C<br>A<br>B<br>C' | 94<br>0<br>94<br>94 | 500<br>315<br>250<br>219 | 25<br>24<br>23<br>22 | 0.25<br>0.40<br>0.50<br>0.57 | -1020+94=-926<br>-1020+0=-1020<br>-1020-94=-1114<br>-1250+94=-1156 | 49400<br>70800<br>97000<br>122000 | 19<br>5<br>1<br>0 | 5<br>1<br>0<br>0 | $\frac{1}{2}$ | 12.0<br>3.0<br>0.5<br>0 | 9 | 2.5 | 0.5 | 0 |
| |  | B<br>C<br>A<br>B' | 54<br>54<br>-108<br>54 | 500<br>315<br>250<br>219 | 25<br>24<br>23<br>22 | 0.25<br>0.40<br>0.50<br>0.57 | -1020+54=-966<br>-1020+54=-966<br>-1020-108=-1128<br>-1250+54=-1196 | 51600<br>67000<br>98100<br>126000 | 17<br>6<br>1<br>0 | 5<br>1<br>0<br>0 | $\frac{1}{2}$ | 11.0<br>3.5<br>0<br>0 | 7.5 | 3 | 0.5 | 0 |

Fig. 8. Comparative data covering different insulation and circuit arrangements

number of 2 phase-to-ground flashovers depends upon the tower footing resistance, increasing with higher footing resistances.

Compared with wood pole lines, it may be seen that the flashovers involving more than one phase are only a third as many; although the total flashovers are more. However, there are many systems capable of retaining stability on a line-to-ground fault, but unable to withstand a 2 or 3 line-to-ground fault. For this reason, grounding the hardware may greatly increase reliability.

*III. Steel Tower Line With Ground Wire.*—The insulator flashover voltage is now 1,130 kilovolts, because reflections from adjacent towers greatly reduce the duration of the surge. Insulator flashover kilovolts, as a function of the span length, is taken from the upper part of figure 5.

The midspan flashovers are calculated from figure 7, where:

$$\alpha = \frac{0.750}{1.000} = 0.75 \qquad \alpha I = 53{,}000$$

$$t = 1 + \frac{0.75}{2} = 1.375 \qquad I = 70{,}000$$

$$s = 15 \qquad \text{Per cent} = 5$$

The correlation factor is 0.5, that is, half the total strokes are charged to midspan.

Although the tower footing resistance is rather high (30 ohms) the ground wire has reduced the flashovers to about 7 per cent, with only 2 per cent involving 2 phases. Although no 3 phase flashovers are calculated, there is a possibility that some of the calculated 2 phase flashovers in reality would be simultaneous 3 phase flashovers. With higher tower footing resistances there will be a greater proportion of 2 and 3 phase flashovers.

*IV. Double Circuit Line Without Ground Wire.*—Each circuit is assumed to have 9 insulator units. On an average, about 20 per cent of the strokes involve both circuits. The effect of normal frequency polarity in determining a double circuit outage is very pronounced. The type of fault is tabulated without regard to whether one or both circuits are involved.

*V. Double Circuit Line With Ground Wire.*—The flashovers are nearly all single phase, although involving the same phase of both circuits in a quarter of the cases. The midspan flashovers are the same as in case III. Better performance could be obtained with lower tower footing resistance and a higher ground wire clearance.

*VI. Double Circuit Line With Ground Wire and Differential Insulation.*—The instantaneous normal frequency voltage determines which insulator will flashover, other things being equal. McEachron[18] has pointed out that if the insulation of one circuit exceeds that of the other circuit by an amount equal to *twice* the crest value of the normal frequency voltage all 3 phases of the circuit of reduced insulation are certain to flash over before the other circuit becomes involved. Theoretically, an insulation differential greater than 1.73 times normal crest voltage should be sufficient, but to allow for differences in coupling between the conductors it is advisable to allow for an insulation differential of at least 2 times. On a 132 kilovolt circuit this requires at least 2 disks differential. Accordingly, in this example one circuit is assumed insulated with 8 units and the other circuit with 10 units, the total number of insulators being the same as in case V. The total flashovers exceed those in case V, but the differential insulation has restricted them to one circuit.

This scheme of differential insulation has been used by the Pennsylvania Water and Power Company, and also in connection with the application of expulsion gaps[17] to 1 of 2 circuits on the same tower. Expulsion gaps must be used in combination with a ground wire in such an application, and of course some outages may occur on the unprotected circuit due to midspan flashovers, unless the unprotected circuit has greater midspan clearance with respect to the ground wire than the protected circuit.

It has not previously been pointed out that the dominating influence in preventing the spread of flashovers to the more highly insulated circuit is the great increase in the coupling, as additional conductors become involved. It is clear that a small reduction in tower footing resistance would make differential insulation unnecessary.

### FREQUENCY WITH WHICH A LINE IS STRUCK BY LIGHTNING

This study has been restricted to determining the number of flashovers as a percentage of the number of times that the line is struck by lightning. No attempt has been made to predict the actual number of strokes to the line. Estimates based upon storm severity charts appear to be not very conclusive because local topography, storm routes, and line exposure are so difficult to evaluate. It is believed that the best procedure is to compute the percentage of outages by the methods of this paper, and then, by comparing with the operating record of that line, to determine the number of times that the line was hit. For example, suppose that a new line is contemplated and it is desired to know how many times it will be hit. If there is an existing line in the same territory, and if this line is known to suffer an average of 1.2 flashovers per circuit mile per year, and the calculated flashovers are 14 per cent the number of hits per circuit mile per year is 1.2/0.14 = 8.5.

## Appendix I—Line Parameters

The self surge impedance for a single conductor, taking into account corona and ground currents, is given by:[5]

$$Z = 60\sqrt{\log_e\left(\frac{2H}{R}\right)\log_e\left(\frac{2h}{r}\right)} \tag{1}$$

where

$H$ = height of conductor above ground
$2h$ = distance between conductor and its current image in the ground
$R$ = corona radius around the conductor
$r$ = radius of the metallic conductor

It will be sufficient to take[6]

$$h \cong H + 40$$

because the maximum crest values of the surge generally occur within the first microsecond or so.

If $h = H$ (zero resistance ground) and $R = r$ (no corona), equation 1 reduces to the familiar form[7]

$$Z = 60 \log_e\left(\frac{2H}{r}\right) \tag{2}$$

The corona radius $R$ (in inches) depends upon the voltage, and is found from the equation[8]

$$(Kv) = 76R\log_e\left(\frac{2H}{R}\right) \tag{3}$$

The mutual surge impedance is given by[5]

$$Z' = 60\sqrt{\log_e\left(\frac{a}{b}\right)\log_e\left(\frac{A}{b}\right)} \tag{4}$$

where

$b$ = distance between wires
$a$ = distance from one wire to current image of the other
$A$ = distance from one wire to voltage image of the other

The coupling factor is defined as[7]

$$F = \frac{\text{(voltage induced on an adjacent wire)}}{\text{(voltage of the main surge)}} = \frac{Z'}{Z} \tag{5}$$

The surge impedance of $n$ conductors in parallel is[7]

$$Z_n = \frac{Z + (n-1)Z'}{n} \tag{6}$$

where $Z$ is the average self impedance, and $Z'$ the average mutual impedance of the wires. The mutual impedance $Z'$ of $n$ conductors with respect to an adjacent conductor is the average of the mutual impedances of each conductor of the group with the adjacent conductor,[7] and therefore the coupling factor is

$$F = \frac{Z'}{Z_n} \tag{7}$$

Thus when a flashover between conductors parallels their impedances, the net surge impedance decreases while the coupling increases.

## Appendix II—Effect of Normal Frequency Polarity

Referring to figure 3*A*, there is illustrated a lightning stroke of surge impedance $Z_0$ contacting a line conductor of surge impedance $Z_1$ and instantaneous normal frequency voltage $e_1$. This voltage $e_1$ is the equivalent of a pair of oppositely moving traveling waves $e_1/2$. When the stroke makes contact with the line conductor these waves $e_1/2$ impinge on $Z_0$ from both sides, and the resulting voltage therefore is

$$\left(\frac{2Z_0}{Z_0 + Z_1/2}\right)\frac{e_1}{2} = \frac{2Z_0}{2Z_0 + Z_1}\,e_1 \cong \frac{e_1}{2} \tag{8}$$

and the normal frequency voltage of the stricken conductor number 1 with respect to number 2 is

$$e = \frac{e_1}{2} - e_2 \tag{9}$$

Now, if the lightning has contacted 2 conductors as indicated in figure 3*B*, the analysis is quite similar, except that the surge impedance is for 2 conductors in parallel (number 1 and number 2) and the equalized normal frequency voltage on the stricken conductors becomes

$$\left(\frac{2Z_0}{Z_0 + Z_2/2}\right)\left(\frac{e_1 + e_2}{4}\right) = \frac{Z_0(e_1 + e_2)}{2Z_0 + Z_2} = \frac{-Z_0 e_3}{2Z_0 + Z_2} \cong -\frac{e_3}{3} \tag{10}$$

and the normal frequency voltage of the stricken pair with respect to conductor number 3 is

$$e = -\frac{e_3}{3} - e_3 = -\frac{4}{3}\,e_3 \tag{11}$$

If 3 conductors are contacted, the normal frequency voltage cancels, because on a balanced 3 phase circuit

$$e_1 + e_2 + e_3 = 0$$

If the lightning contacts a ground wire, or tower, the voltage with respect to a line conductor of instantaneous voltage $e$ is simply $-e$.

If 1 or 2 line conductors flash over to a tower, the surge impedance $Z_0$ of the stroke used in equations 8 and 10 is replaced by

$$\frac{1}{1/Z_0 + 1/R + 2/Z_g} \tag{12}$$

where

$R$ = tower footing resistance
$Z_g$ = surge impedance of the ground wires

Ordinarily, the tower footing resistance is small enough so that for all practical purposes the normal frequency voltage vanishes.

## Appendix III—Lightning Current to Cause Flashover

If the lightning voltage of the free traveling wave coming down the stroke is $e_0$ and if $I$ is the current which this stroke would discharge into a zero resistance ground, then

$$e_0 = \frac{1}{2}\,Z_0 I \tag{13}$$

and therefore the surge voltage appearing on the stricken conductors is

$$E = \frac{2Z_n}{Z_n + 2Z_0}\,e_0 = \frac{Z_n Z_0}{Z_n + 2Z_0}\,I \tag{14}$$

where $Z_n$ is the surge impedance of all contacted conductors in parallel, the subscript $n$ designating the number of conductors involved.

The total voltage between the stricken group of conductors and an adjacent clear conductor is

$$V = E(1 - F_n) + e \tag{15}$$

where $F_n$ is the coupling factor defined in appendix I and $e$ is the normal frequency voltage defined in appendix II. Therefore, if $V$ is the net voltage necessary to flash over the insulators, the surge must reach a value

$$E = \frac{V - e}{(1 - F_n)} \tag{16}$$

or, by equation 14, the lightning current necessary to cause a flashover, based upon a zero resistance ground, must be

$$I = \left(\frac{1}{Z_0} + \frac{2}{Z_n}\right)\left(\frac{(V - e)}{(1 - F_n)}\right) \tag{17}$$

If, however, the stroke is to a tower, the tower footing resistance $R$ is in parallel with the surge impedance $Z_n/2$ of the conductors involved, and equation 17 becomes

$$I = \left(\frac{1}{Z_0} + \frac{2}{Z_n} + \frac{1}{R}\right)\frac{(V - e)}{(1 - F_n)} \tag{18}$$

Thus, in any case, the lightning current necessary to cause insulator flashover is given by an equation of the form

$$I = \frac{(V - e)}{R'(1 - F_n)} \qquad (19)$$

where $R'$ is an *equivalent resistance*, taking into account the impedances of the lightning stroke, tower footing resistance, and connected conductors; and which has the effect of reducing the calculated lightning current to that which the stroke could deliver to a zero resistance ground.

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# Torque in a Bipolar Induction Meter

**A method of computing the torque developed in a bipolar induction watt-hour meter, based upon the actual eddy current distribution in the disk, is presented herewith. A comparison between measured and computed torque for a model meter is included.**

By
**RALPH M. MORTON**
ASSOCIATE A.I.E.E.

Vancouver, B. C.
Canada

IN ORDER to compute the torque of an induction watt-hour meter, the magnitude and direction of the currents induced in the moving element must be known. It usually is assumed that these currents flow around the inducing pole in a series of concentric rings. This assumption is valid when the center of the pole coincides with the center of the disk, but not when the pole is located eccentrically with respect to the disk axis. The object of this paper is to investigate the path of the eddy currents induced in a disk, and to develop a torque formula based upon the actual current distribution.

### Current Distribution

Consider a pair of equal "point" alternating magnetic fields 180 degrees out of phase with each other, normal to an infinite conducting sheet. It can be shown (see appendix) that the path of the currents induced in the sheet is a series of circles, as shown in figure 1, and that the relation between

$s$ = the half distance between poles
$r$ = the radius of any flow circle
$e$ = the eccentricity of the center of that circle

is given by

$$s = \frac{r^2 - e^2}{2e} \qquad (1)$$

$$e = \sqrt{s^2 + r^2} - s \qquad (2)$$

It should be noted that $s$ is the parameter defining an entire family of current flow circles, and that if $r$ and $e$ are known for any one circle, the entire series can be described.

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A paper recommended for publication by the A.I.E.E. committee on instruments and measurements. Manuscript submitted July 1, 1935; released for publication Dec. 16, 1935.

The experimental work in connection with this paper was done in the electrical laboratories of the University of British Columbia, Vancouver.

Consider a single alternating point magnetic field located eccentrically with respect to the center of a conducting disk. Then the boundary of the disk defines one flow circle and by means of equation 1 the entire series can be drawn. In order to facilitate the drawing of flow circles through a given point, the following graphical method is useful: Refer to figure 2, which is the plan of a disk with its 2 driving magnets. Measure $e_0$ and $r_0$, calculate $s$ by equation 1, and draw $CD$. In order to draw a flow circle through the point $y$, proceed as follows: With centers $x$ and $y$, draw arcs intersecting at $m$ and $n$; project $mn$ to intersect $CD$ at $p$; draw $yt$ at right angles to $yp$. Then $t$ is the center of the flow circle through $y$.

The equipotential lines are the orthogonal trajectories of the flow circles, and can be shown to be a series of circles having their centers on the line $CD$ and passing through the center of the pole.

The preceding work was based upon the use of point poles. These point poles do not coincide with the geometrical center of poles of finite dimensions.

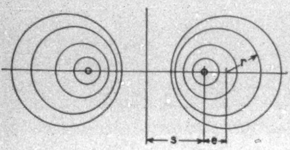


**Fig. 1. Paths of current induced in an infinite conducting sheet by a pair of equal "point" alternating magnetic fields 180 degrees out of phase with each other**

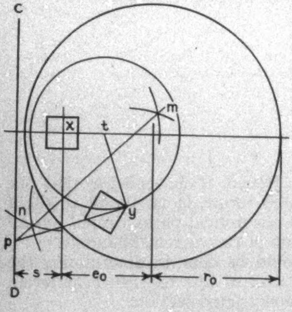


**Fig. 2. Plan of watt-hour meter disk showing methods of drawing eddy current flow circles**

Refer to figure 5. The center of the actual pole is at $K$, and $r_p$ is the radius of a circular pole of equal area. The point pole, equivalent to the actual pole, is located at $j$, at a distance $x$ from $K$. It can be shown (see appendix) that

$$x = \frac{(r_0^2 - r_p^2 - e_0^2) - \sqrt{(r_0^2 - r_p^2 - e_0^2)^2 - 4e_0^2 r_p^2}}{2e_0}$$

Then

$$s = \frac{r_0^2 - (e_0 + x)^2}{2(e_0 + x)} \tag{3}$$

In order to obtain some experimental check on the preceding work, a shallow circular trough of mercury was set up together with an a-c magnet as shown in figure 3. Two pointed electrodes made contact with the mercury and were connected by shielded leads to a tuned vibration galvanometer, provision being made for moving these contacts and plotting their positions. A plot of the equipotential lines obtained with this apparatus is given in figure 4. The theoretical equipotential curves are drawn in full, while the experimental points are shown by small circles.

## CALCULATION OF TORQUE

The preceding work indicates the path of the induced currents. The next step is to develop torque relations based upon this current distribution. Let

$f$ = supply frequency
$\phi_a$ = effective flux in gap of magnet $a$
$\phi_b$ = effective flux in gap of magnet $b$
$\theta$ = phase angle between $\phi_a$ and $\phi_b$
$R_b$ = equivalent resistance of eddy current path under pole $b$
$X_b$ = equivalent reactance of eddy current path under pole $b$
$A$ = area of each pole allowing for flux fringing
$L$ = length of current path under pole $b$
$P$ = mean radius of action
(All dimensions are in centimeters.)

$$\text{The torque} = \frac{1}{1 + \left(\frac{X_b}{R_b}\right)^2} \times \frac{0.4\,\pi f \phi_a}{R_b} \times \frac{\phi_b}{A} \times LP \sin\theta \times 10^{-8} \text{ dyne-cm}$$

At commercial frequencies $(X/R)^2$ is small, and the first factor in the right-hand member can be neglected. It is necessary to find $R_b$, $P$, and $L$. A plan of the disk and its driving magnets is drawn to scale in figure 5.

Measure $e_0$ and $r_0$ and calculate $s$ from equation 3; draw $CD$. By means of the construction illustrated in figure 2, draw several flow lines across the pole face, dividing it into 7 or 8 zones. It may be noted that the current density, direction of flow, and length of path under the pole varies in each zone, and it is necessary to compute the torque due to each zone separately.

## CALCULATION OF ZONE RESISTANCE $R$

Consider zone $abcd$ in figure 5. Let

$r_1$ = radius of arc $ab$
$r_2$ = radius of arc $cd$

**Fig. 3. Apparatus for determining paths of eddy currents produced in a shallow circular trough of mercury by an a-c magnet**

$e_1$ = eccentricity of arc $ab$ (calculated from equation 2)
$e_2$ = eccentricity of arc $cd$ (calculated from equation 2)
$s$ = distance between point pole and line $CD$
$t$ = thickness of disk
$\rho$ = resistivity of disk in microhms per centimeter cube
(All dimensions are in centimeters.)

The resistance of the eddy current path through the zone is given (see appendix) by:

$$R_z = \frac{2\pi\rho}{2.303t} \times \frac{1}{\log_{10} \dfrac{\dfrac{2s}{r_1 - e_1} - 1}{\dfrac{2s}{r_2 - e_2} - 1}} \text{ microhms}$$

### Calculation of Radius of Action, $P$

With center $q$, draw the flow circle $mn$ through the middle of the zone and bisect $mn$ at $p$. Then $pq$ is the line of action of the force developed by the zone, and the radius of action is $uv$.

### Calculation of Mean Length of Path, $L$

The component of force developed by the zone along the line of action $pq$ is proportional to:

$$2\int_0^\alpha r_3\, d\alpha \cos\alpha = 2r_3 \sin\alpha = mn = L$$

In order to check the preceding theory, an aluminum disk, mounted on a vertical axis in jewel bearings, was fitted with a calibrated torsion head, as shown in figure 6. The torque developed by the disk under the influence of 2 magnets connected to a 2 phase supply was measured. The magnitude and phase angle of the flux in the air gap of each magnet was measured by means of search coils wound on the pole tips and connected to an a-c potentiometer. The results obtained with this apparatus are given in table I. In each case the calculated torque is less than the measured torque, the error increasing as the pole angles increase, and as the poles approach the disk edge.

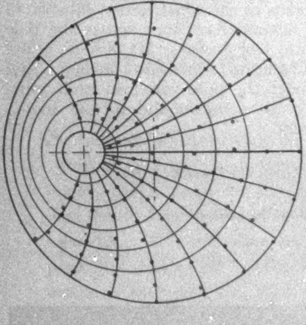


Fig. 4. Equipotential lines obtained with apparatus shown in figure 3

$R_0$ = 4.5 inches
$e$ = 2.1 inches
$s$ = 3.77 inches

The torque was computed on the basis that the current paths are determined solely by resistance, and the experimental check was made using a mercury disk. The torque tests were made on a disk of aluminum having a specific resistivity about 3 per cent of the value for mercury. This means that any deviation from the theoretical flow lines caused by self and mutual inductance of the current filaments would be greatly magnified in the aluminum disk. Inasmuch as the major part of the zone resistance is concentrated in the section between the pole and the disk edge, any slight deviation from the theoretical paths in this section would have a great influence on the magnitude of current flow, and hence on the torque.

In test 6, the width of the entire current path under the pole is about 25 millimeters. This path at the constricted section is reduced to approximately 0.1 millimeter. The ratio 25 to 0.1 is a rough measure of the extent to which the resistance is concentrated in the constricted section and is a function of both pole angle and edge distance, decreasing as the pole angle decreases and as the poles recede from the edge of the disk. Hence, it is probable that the error in the calculated torque is ascribable to slight deviations from the theoretical paths caused by self and mutual induction of the current filaments.

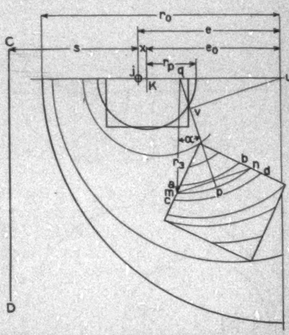


Fig. 5. Plan of watt-hour meter disk and its driving magnets, illustrating method of computing torques

Further work should be done in determining the current paths in a disk of low resistance material, particularly in the constricted section.

## Appendix

### Eddy Current Path

Consider an alternating magnetic point field normal to an infinite sheet of conducting material of resistivity $\rho$ and thickness $t$. Then the resistance of an annular ring of outer radius $r_2$ and inner radius $r_1$ is

$$\frac{2\pi\rho}{t} \times \frac{1}{\log_e \dfrac{r_2}{r_1}}$$

Next consider a pair of such fields 180 degrees out of phase with each other as in figure 7. Let $P$ move in the direction of the resultant field and let $F$ be on the locus of $P$. The co-ordinates of $P$ are $x$ and

## Table I—Comparison of Measured and Computed Torques

| Test | Angle Subtended at Center of Disk by Pole Centers, Degrees | Distance Between Edge of Pole and Disk Edge, Millimeters | Measured Torque, Dyne-Centimeters | Computed Torque, Dyne-Centimeters | Ratio of Computed to Measured Torque, Per Cent |
|---|---|---|---|---|---|
| 1 | 65 | 17 | 5,300 | 4,600 | 87 |
| 2 | 65 | 12 | 4,760 | 3,440 | 72 |
| 3 | 65 | 6 | 3,710 | 2,190 | 59 |
| 4 | 90 | 17 | 4,550 | 3,900 | 86 |
| 5 | 90 | 12 | 4,050 | 2,840 | 70 |
| 6 | 90 | 6 | 3,080 | 1,560 | 50 |

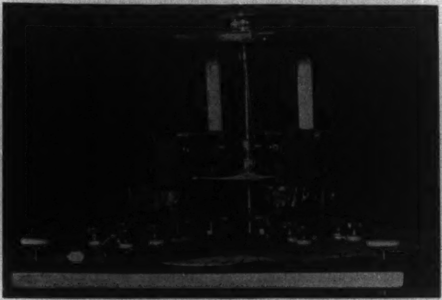


Fig. 6. Model meter disk and driving magnets used to check computed and measured torque

$y$. Since $PF$ is the locus of $P$, there can be no resultant current crossing $PF$. Current crossing $PF$ induced by pole $A$

$$I_a = \frac{Et}{2\pi\rho} \log_e \frac{r_a}{m}$$

Current crossing $PF$ induced by pole $B$

$$I_b = \frac{-Et}{2\pi\rho} \log_e \frac{r_b}{n}$$

The resultant current $I_a + I_b$ must be zero; therefore

$$\frac{Et}{2\pi\rho}\left[\log_e \frac{r_a}{m} - \log_e \frac{r_b}{n}\right] = 0$$

$$\frac{r_a}{r_b} = \frac{m}{n}$$

Now

$$r_a^2 = (s + x)^2 + y^2$$

$$r_b^2 = (s - x)^2 + y^2$$

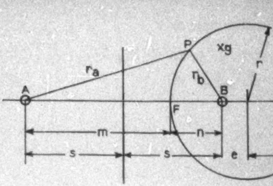
$$y^2 + \left[x - \frac{m^2 + n^2}{2(m - n)}\right]^2 = \frac{m^2n^2}{(m - n)^2}$$

This is the equation of a family of circles of radius $\frac{mn}{m - n}$ having their centers at

$$x = \frac{m^2 + n^2}{2(m - n)}$$

$$y = 0$$

Fig. 7. Diagram illustrating method of calculating eddy current path



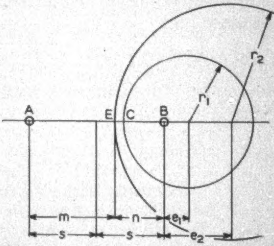


Fig. 8. Diagram illustrating method of calculating zone resistance

Further,

$$e = x - s$$

$$= \frac{m^2 + n^2}{2(m - n)} - \frac{m + n}{2} = \frac{n^2}{m - n}$$

$$m = 2s - r + e$$

$$n = r - e$$

Therefore,

$$e = \sqrt{s^2 + r^2} - s$$

$$s = \frac{r^2 - e^2}{2e}$$

### ZONE RESISTANCE

The current in the zone $EC$ in figure 8 can be found by adding the separate currents in the zone due to each pole.

$$I_a = \frac{Et}{2\pi\rho} \log_e \frac{AC}{AE}$$

$$I_b = \frac{Et}{2\pi\rho} \log_e \frac{BE}{BC}$$

$$I_a + I_b = \frac{Et}{2\pi\rho} \log_e \frac{BE}{BC} \times \frac{AC}{AE}$$

$$= \frac{Et}{2\pi\rho} \log_e \frac{(r_2 - e_2)\,(2s + e_1 - r_1)}{(r_1 - e_1)\,(2s + e_2 - r_2)}$$

$$\text{Conductance} = \frac{t}{2\pi\rho} \log_e \frac{\dfrac{2s}{r_1 - e_1} - 1}{\dfrac{2s}{r_2 - e_2} - 1}$$

$$\text{Resistance} = \frac{2\pi\rho}{2.303t} \times \frac{1}{\log_{10} \dfrac{\dfrac{2s}{r_1 - e_1} - 1}{\dfrac{2s}{r_2 - e_2} - 1}}$$

CALCULATION OF $x$

Refer to figure 5. For all circles,

$$s = \frac{r^2 - e^2}{2e}$$

$$e = (e_0 + x)$$

Therefore,

$$\frac{r_0^2 - (e_0 + x)^2}{2(e_0 + x)} = \frac{r_p^2 - x^2}{2x}$$

from which

$$x = \frac{(r_0^2 - r_p^2 - e_0^2) - \sqrt{(r_0^2 - r_p^2 - e_0^2)^2 - 4e_0^2 r_p^2}}{2e_0}$$

# The Influence of James Watt on the Central Station Industry

By
**GEORGE A. ORROK**
MEM. AM. SOC. MECH. ENGRS.
Consulting Engr.,
New York, N. Y.

WITH the conception and installation of the Pearl Street station in September 1882 in New York, the electric light and power industry became a fact, and from such small beginnings a mighty industry has developed. A few weeks later the Appleton, Wisconsin, plant was started. The Appleton generators were driven by a waterwheel, and its successors using the same prime mover dominate about a third of the central station industry. But Mr. Edison with a conception of a universal system of light and power supply saw with clear vision the possibilities of the steam engine as a prime mover, and located his generating stations as nearly as possible in the center of distribution. . . independent of weather or rainfall or the presence of flowing water, he chose and adopted for his purposes the steam engine which Newcomen had invented and James Watt had perfected and adapted to the transmission of power through a rotating shaft.

This prime mover which Watt at the beginning of the nineteenth century had left practically complete (the only major improvement since that time being the Corliss valve), held sway for a full century as the only independent source of power that could be located anywhere, and it was on Watt's inventions that the central station industry was built up and spread to the uttermost ends of the earth.

One of the 6 major inventions or discoveries of Watt was a knowledge of the expansive force of steam. The application of this principle made the steam engine an economical source of power, and, as the years rolled by, this principle became the base of a system of power generation which has replaced to a large extent Watt's reciprocating engine by a fluid velocity engine, the steam turbine. The 35 years of this century have seen the development of this new prime mover to enormous size, 225,000 of Watt's horsepowers in a single unit, and to a volume exceeding 150,000,000 horsepower. This development may be partly attributed to Watt who made clear to all men the principle of the expansive force of steam.

Watt's career was based on experimentation. What he did not know he immediately tried, working continuously from failure to success, and Edison and the Central Station Industry have built their successes on the same principle. From its earliest beginnings the central station industry has never been content to take things as they are; witness Edison in 1881 starting Wheeler on a model of his distribution system to find out what actually was needed in copper, thus doing what Watt did with his steam jacket and separate condenser. From this model Edison gained facts which, leading to further experimentation, gave him the idea of the 3 wire system which saved 65 per cent of the copper investment in distribution systems. Edison hunted for a means to measure the electric current, so he gave us the chemical meter, and other inventors followed with the indicating and recording instruments, again using Watt's lead in finding a measure for power and producing the engine indicator. Only a day or two ago, the air was full of a report by President Compton of the Massachusetts Institute of Technology on a National Research Problem similar to Watt's work from 1765 to 1785 on his prime mover. We perhaps do not consciously look back to the Glasgow University instrument maker, but the whole central station industry is emulating his example and applying experimental knowledge to the improvement in every possible way of central station service.

Playfair, a contemporary of Watt, is quoted by Stuart more than 100 years ago as follows:

"It would be difficult to estimate the value of the benefits which these inventions have conferred upon the country. There is no branch of industry that has not been indebted to them, and in most all the material they have not only widened most magnificently the field of its exertion, but multiplied a thousand fold the amount of its productions. . . . It has armed the feeble hand of man, in short, with a power to which no limits can be assigned, completed the dominion of mind over matter, and laid a sure foundation for all those future miracles of mechanic power which are to aid and reward the labor of after generations."

. . . two hundred years after the birth of James Watt and 100 years after this appreciation of Watt's solution of the power problem, (we) may wonder at the clear vision, the breadth of view, which could prophesy so truly the triumphs of our power civilization.

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An address delivered at a joint meeting of the Franklin Institute, the Newcomen Society, and the American Society of Mechanical Engineers held in Philadelphia, Pa., January 21, 1936, upon the occasion of the observance of the 200th anniversary of the birth of James Watt. Published with the permission of the Franklin Institute and at the request of the A.I.E.E. committee on education.

# Impedance Measurements on Underground Cables

By
R. L. WEBB
MEMBER A.I.E.E.

O. W. MANZ, JR.
MEMBER A.I.E.E.

Both of Brooklyn (N. Y.) Edison Company, Inc.

**To eliminate uncertainties arising from assumed constants involved in the calculation of sequence impedances, field measurements of 60 cycle positive and zero sequence impedances of 2 sizes of 3-conductor underground power cable were made on the 27 kv system of a large eastern metropolitan company; the results are reported in this paper. While the principal results are applicable only to the particular system involved, they show that without the support of the experimental data the calculation of zero sequence impedance of feeder circuits in a system of this kind can be at best only roughly approximate.**

IN A metropolitan transmission system where high voltage underground cable is used extensively, the calculation of fault currents that can exist for the various possible conditions of short circuit is an important phase of protective relay practice. Fault calculations involving balanced 3-phase currents are comparatively simple, and, since the circuit constants usually are known with a fair degree of accuracy, reliable results readily may be obtained. For unbalanced faults, however, the calculations are more complex. If a grounded neutral is involved, the presence of a ground return in the circuit requires additional circuit information—zero sequence impedance—which for power cable circuits usually is difficult to compute. In an effort to eliminate the uncertainty from the assumed constants involved in the calculation of zero sequence impedances by obtaining actual impedance data on its transmission cables, the Brooklyn Edison Company made a series of tests on its 27 kv underground system. It is with the impedance measurements made during these tests that this paper is concerned.

## Description of Underground System

The Brooklyn Edison Company's 27-kv 60-cycle transmission system is entirely underground and comprises approximately 650 miles of cable,[1] of which more than 75 per cent is of the 3-conductor shielded type. The transmission cables, besides feeding substations and serving as generating station interconnections, feed the many transformers of the networks[2] which comprise the main method of secondary distribution throughout Brooklyn's 80 square mile area. At Hudson Avenue station[3] the generator and autotransformer neutrals are connected solidly to the station ground bus, which is bonded to water mains in the vicinity. Throughout the underground plant, all cable sheaths are bonded together at each manhole, to metal supports, and to the bare neutral conductor in areas having underground distribution. It is the company's practice to ground the neutral conductor to a water pipe at each service.

## Selection of Feeders for Test

Application of the method of symmetrical components[4] to the calculation of system faults was limited in its accuracy, as previously noted, by the lack of accurate zero sequence impedance data. Five feeders therefore were selected according to cable type and location so that experimental data might be obtained to indicate the variation in the zero sequence impedance of a given cable type with changes in the character of the ground return path and with changes in current magnitude. It was desired also to determine the positive sequence impedance of the 2 sizes (350,000 and 500,000 circular mils) of 3-conductor shielded cable most commonly used on the system. Figure 1 shows the routes of the feeders selected for test. The short circuit and ground points, designated in the figure by X, were established by closing the network transformer grounding switches, except in the 2 cases where feeders were grounded in substations.

## Test Procedure

Sources of supply were made available at Hudson Avenue station, where the use of the feeder test busses and associated equipment afforded a convenient connection to the feeders leaving the station. Since virtually all of each cable under observation had steel binding tape, it was necessary to provide sufficient generator capacity to measure the zero sequence impedance at currents of approximately 200 amperes per conductor, preliminary calculations having indicated that at low currents complete saturation of the magnetic tape would not have been obtained. Two 60-cycle generators were available: one, a delta-connected 2,300-volt 6,000-kva machine; the other, a 5-kva star-connected 120-volt generator. Positive sequence impedances were measured at approximately 250 amperes per phase. Phase differences between the voltages and currents were deter-

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1. For all numbered references, see list at end of paper.

mined through the use of an a-c potentiometer[5] which afforded voltage and current readings to within 1 per cent, and phase differences to within 0.5 degree. Figure 2 is a schematic diagram of the test connections for the measurement of zero sequence impedance.

## TEST RESULTS

For graphical presentation, the results obtained on feeder 25-99-11 (figure 3) have been selected as typical of the 4 feeders made up of the 350,000 circular mil cable. As shown in figure 1, feeder 25-99-11 extends some 3 miles from Hudson Avenue to a point where it separates into 2 branches. The feeder length from Hudson Avenue to the end of the east branch is 36,800 feet, and to the end of the south branch, 31,000 feet. Except for 450 feet of 500,000 circular mil cable in test length 7, the feeder consists of 350,000-circular mil 3-conductor shielded cable, with 350 mils of paper insulation per conductor, and a lead sheath 140 mils thick. The outside diameter of the cable is approximately 3 inches. The conductors are sector shaped, and the binding tapes are of steel. The average length of cable between manholes, wherein oil filled joints are located, is 200 feet.

To avoid repeated use of the lengthy phrases by which the various quantities under discussion are known, the following symbols have been used in the remainder of the paper, where convenient:

$r_1$, $x_1$, $z_1$—positive sequence resistance, reactance, and impedance, respectively, per phase per unit length of circuit .

$r_0$, $x_0$, $z_0$—zero sequence resistance, reactance, and impedance, respectively, per phase per unit length of circuit

$r_s$, $x_s$, $z_s$—"internal" self-resistance, reactance, and impedance, respectively, per phase per unit length of circuit, of a cable's 3 conductors in parallel measured at the outer surface of the cable sheath

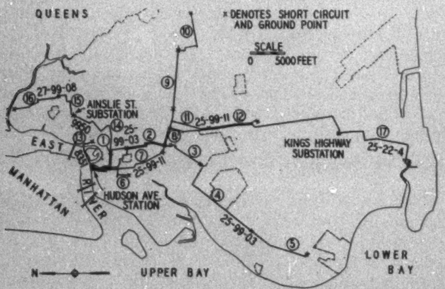
QUEENS
× DENOTES SHORT CIRCUIT AND GROUND POINT
SCALE
0 5000 FEET
27-99-08
AINSLIE ST. SUBSTATION
9950
25-99-03
25-99-11
25-99-11
KINGS HIGHWAY SUBSTATION
25-22-4
EAST
RIVER
8351
MANHATTAN
HUDSON AVE. STATION
25-99-03
LOWER BAY
UPPER BAY
N
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17

Fig. 1. Outline map of Brooklyn, showing locations of 27 kv transmission feeders selected for test

For the representation of total quantities, as distinguished from quantities per unit length, the lower case letters in the foregoing notation have been replaced by capitals:

$R_e$, $X_e$, $Z_e$—total "external" resistance, reactance, and impedance, respectively, of a ground-return feeder circuit in which the cable's 3 conductors are in parallel. For a given circuit length $Z_e = {}^1/_3(Z_0 - Z_s)$

The average value of $z_1$ at 60 cycles for feeder 25-99-11, as obtained from the slopes of the $R_1$ and $X_1$ curves in figure 3, was $0.0334 + j\,0.0402$ ohm per phase per 1,000 feet (corrected to 25 degrees centigrade). The average values of $R_0$ and $X_0$ proved to be approximately $4^1/_2$ and $3^1/_2$ times the respective positive sequence components for this particular feeder. The zero sequence curves also clearly indicate the branch point of the feeder, since the values of the components for each branch are slightly different. The resistance curves approximate straight lines, with the east branch having the higher value of $r_0$. This condition probably corresponds to the fact that the east branch lies in an area where the duct bank occupancy is not very great, and the ground return path contains fewer metallic conductors in parallel with the feeder's own sheath, although the percentage difference in unit resistance of the 2 branches is not as great as the percentage difference in effective cross section of the metallic conductors in their respective return paths. Conversely, the zero sequence reactance of the east branch is the lower. Although the values of $x_0$ for both branches increase slightly with circuit length from Hudson Avenue, there is some indication that for circuit lengths beyond 30,000 feet the reactance curves would tend to straighten out.

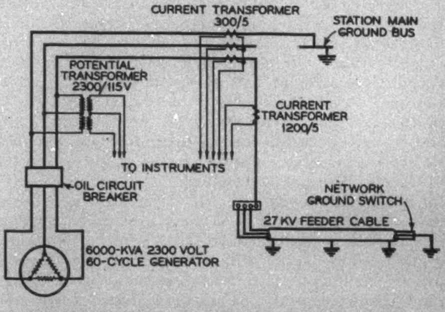
CURRENT TRANSFORMER 300/5
STATION MAIN GROUND BUS
POTENTIAL TRANSFORMER 2300/115V
CURRENT TRANSFORMER 1200/5
TO INSTRUMENTS
OIL CIRCUIT BREAKER
NETWORK GROUND SWITCH
27 KV FEEDER CABLE
6000-KVA 2300 VOLT 60-CYCLE GENERATOR

Fig. 2. Diagram of connections at Hudson Avenue station for zero sequence impedance measurements

To demonstrate the magnetic effect of the cable's steel binding tape on the impedance of this size and type of cable, measurements of $z_1$ and $z_0$ were made on the full length (46,800 feet) of feeder 25-99-03 at various current values. These results are shown in figure 4; it may be noted that the positive sequence components were practically unaffected by changes in current magnitude. For this feeder, $z_1$ at 240 amperes per phase was found to be $0.0334 + j\,0.0412$ ohm per phase per 1,000 feet (corrected to 25 degrees centigrade). This value is in substantial agreement with the one obtained for feeder 25-99-11.

The effect produced on the zero sequence impedance characteristics by the presence of the steel tape is pronounced; it is evident that in the calculation of circuits involving cable of this type, saturation of the steel may be assumed only when the total ground current is in excess of about 600 amperes. It may be noted that the curves of $r_0$ and $x_0$ lack test points in the range between 25 and 75 amperes per conductor. The shapes of the respective curves to be drawn through this current range to complete the characteristic indicated by the 5 test points, were determined by means of auxiliary data secured in the research laboratory on a 45 foot length of a similar cable.

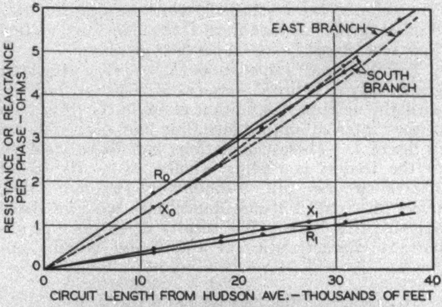

**Fig. 3. Impedance measurements at 60 cycles on feeder 25-99-11**

Average conductor temperature (calculated) during measurements of $R_1$ and $X_1$ was 25 degrees centigrade

Values of $Z_0$ were measured at average current of 190 amperes per conductor; $Z_1$ at average current of 240 amperes per conductor

The laboratory test on the 45 foot sample of 350,000-circular mil 3-conductor shielded cable consisted in determining the cable's "internal" impedance characteristic under 60 cycle current loading. In this test, the use of a fine insulated wire along the surface of the sheath permitted the determination of the "internal" self-impedance[6] ($z_s$) of the 3 paralleled conductors measured at the outer surface of the cable sheath; this quantity included the only part of the total impedance variable with current, in a circuit composed of 3 paralleled cable conductors with ground return and with the sheath grounded at the ends through zero resistance. The results of these "internal" impedance measurements are shown as fine-line curves in figure 4. It was noted that the addition of approximately fixed quantities to the respective "internal" impedance components ($r_s$ and $x_s$) produced 2 similarly shaped curves which would include the series of 5 points plotted from the field test data. These new curves were accepted as the $r_0$ and $x_0$ components of the zero sequence impedance of the feeder for the particular circuit length under investigation, and the nearly constant differences between these curves and the curves of $r_s$ and $x_s$ were regarded as resistance and reactance components of the impedance to zero sequence current of that part of the feeder circuit external to the cable. For convenience of presentation, these latter quantities, which are independent of the current, were divided by 3, and the values resulting from this division were designated arbitrarily as the resistance and reactance components of the feeder circuit's "external" impedance $Z_e$.

Feeder 8351 (figure 1) also was tested with varying current, and the impedance characteristics obtained are shown in figure 5. This feeder is 5,300 feet long and consists entirely of 500,000-circular mil 3-conductor shielded cable, 60 per cent of which is a submarine section having an internal construction similar to that of the underground section, but having an armor over the lead sheath of galvanized steel wire embedded in jute. The $r_0$ and $x_0$ characteristics are similar to those obtained for the 350,000-circular mil 3-conductor underground cable, but the presence of the additional magnetic material of the armor wire greatly increased the current range over which the impedance varied. Since the current limit of the feeder test bus was reached during the test on this feeder before saturation of the steel tape and submarine armoring could be attained, the value of $Z_0$ picked for use in calculations involving this feeder length had to be obtained by extrapolation.

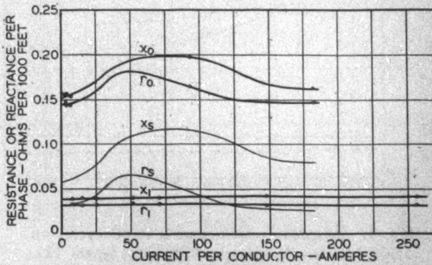

**Fig. 4. Impedance measurements at 60 cycles on 46,800 foot length of feeder 25-99-03 (test lengths 1 + 2 + 3 + 4 + 5)**

Average conductor temperature (calculated) during measurements of $r_1$ and $x_1$ was 22.5 degrees centigrade

For the underground length of 500,000-circular mil 3-conductor shielded cable, which has paper insulation averaging 310 mils in thickness per conductor and a lead sheath 130 mils thick, the calculated value of $z_1$ was $0.0242 + j\,0.0365$ ohm per phase per 1,000 feet (corrected to 25 degrees centigrade).

Against the one value of $z_1$ for the 500,000 circular mil underground cable, there were twelve observations for the 350,000 circular mil size. Although the several feeder lengths contained varying amounts of the type of cable under survey, there were 12 test lengths (3, 5, 6, 7, 8, 9, 10, 11, 12, 15, 16, and 17), comprising a total of 109,000 feet, that were made up entirely (or within 4 per cent) of the smaller-sized shielded cable. The average of their positive sequence impedances was $0.0334 + j\,0.0410$ ohm per phase per 1,000 feet (corrected to 25 degrees centigrade). The basis for correcting the average $r_1$ to the standard temperature was established during the laboratory work on the 45 foot sample, for which the ratio of a-c to d-c resistance at 25 degrees centigrade was found to be 1.071. A review of these positive sequence impedance data indicates general agreement with previous work of this kind except for the reactances, which are approximately 10 per cent lower than those obtained by Salter, Shanklin, and Wiseman[7] for similar types of cable during their investigations on 15 to 20 foot laboratory samples of new cables.

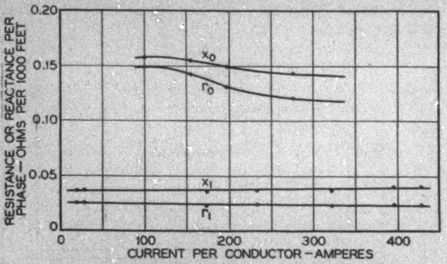

**Fig. 5. Impedance measurements at 60 cycles on 5,300 foot length of feeder 8351 (test length 13); submarine section included**

Average conductor temperature (calculated) during measurements of $r_1$ and $x_1$ was 19.5 degrees centigrade

The variation in $Z_0$ with circuit length from the generating station for feeders consisting of a given type of cable is shown by figure 6, where the ratios $R_0/R_1$ and $X_0/X_1$ have been plotted. The data for these curves were taken from the measurements on feeders 25-99-03 and 25-99-11, which consist of 350,000-circular mil 3-conductor cable. The reactance ratio varied from 2.8 at a circuit length of 7,800 feet to 3.9 at 47,000 feet, whereas the resistance ratio varied between such close limits as to be considered constant from a practical standpoint. Similar data on feeders 27-99-08 and 9,950 (test lengths 14, 15, and 16) were illustrative of the same effects, but the data have not been included in figure 6 since the large percentage of smaller sized cable in test length 14 renders the resistance ratios impossible of direct comparison with those for feeders 25-99-03 and 25-99-11. The reactance ratios, however, would fall well into line with the points on figure 6, since they are not affected much by differences in conductor size so long as the relative spacings undergo no great changes.

Since in the usual methods for computing zero sequence impedance the cable is assumed to be of such length that the end effects are negligible, the reactance as well as the resistance component may be treated as a linear function of circuit length. The experimental data presented in figure 6 indicate that for average underground transmission conditions as they exist in Brooklyn, $X_0$ cannot be so computed unless the circuit length is more than 40,000 feet. In the range of circuit lengths between 0 and 40,000 feet, the variation of $X_0$ with length appears to be exponential in character.

The following tabulation illustrates in another way the effect of location (distance from generating station) on zero sequence impedance:

| Test Length | $+ j x_1$ Ohm per Phase per 1,000 Feet | $r_0 + j x_0$ Ohm per Phase per 1,000 Feet |
|---|---|---|
| 7 | $0.0330 + j0.0420$ | $0.153 + j0.127$ |
| 5 | $0.0334 + j0.0416$ | $0.152 + j0.171$ |

These 2 sections, though parts of different feeders, are composed of the same size and type of cable, and their respective values of $r_0$, as well as their values of $z_1$, were shown to be virtually identical. Their zero sequence reactances, however, were quite different. The value of $x_0$ for section 5, which is approximately 6 miles farther distant from Hudson Avenue station than test length 7, was 35 per cent greater.

The "external" impedances ($R_e + jX_e$), presented graphically in figure 7, were calculated in accordance with the arbitrary definition given in the discussion of the "internal" impedance (fine line) curves shown in figure 4. These calculations had to be confined to the feeders consisting wholly, or nearly so, of 350,000-circular mil 3-conductor shielded cable, since "internal" self-impedance data were available only for that type. The results reveal several important characteristics of the feeder circuits encountered during the zero sequence impedance tests. In spite of the fact that the resistance of the neutral system might be expected to be relatively greater in the outlying districts, the "external" resistance of a feeder circuit is practically a linear function of the circuit length. It follows from this, that in a system of this kind, $r_0$ may be considered constant,

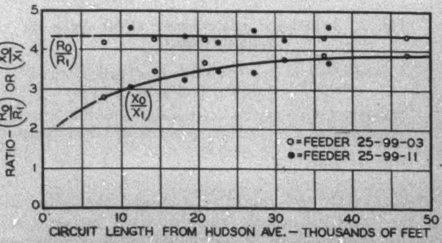

**Fig. 6. Relation between $R_0/R_1$, or $X_0/X_1$, and circuit length from generating station for feeders composed of the same type of cable**

Cable description: 350,000 circular mils; 3 sector conductors; shielded; steel binding tape; 350 mils paper insulation; 140 mils lead sheath; 2,950 mils outside diameter regardless of location. The $R_e$ curve also affords experimental confirmation of the tendency of the ground current to follow the irregularities of the feeder path. As also suggested by the shape of the reactance ratio curve in figure 6, the curving characteristic of $X_e$ shown by figure 7 indicates the effect of having an increasing density of buried metallic structures as the distance from the generating station decreases. The additional paralleling sheaths toward the generating station serve to reduce a feeder's "external" reactance per unit of circuit length, without effecting any noticeable change in the rate at which the "external" resistance varies with circuit length.

The use of these $R_e$ and $X_e$ curves in estimating the zero sequence impedance of circuits for which no field data are available obviously is limited to the feeder system on which the experimental data were taken, since even the diameter of a faulted cable is an important factor among the various field conditions that influence the resultant impedance. So far as earth resistivity is concerned, the number of points available for determining the $R_e$ and $X_e$ curves seemed to include data from enough circuits of different lengths and locations to make the curves adequate for estimating purposes without having to take into account the variations in earth resistivity that probably exist.

### CALCULATIONS

To determine the approximately equivalent make-up of a typical ground return path and the current distribution therein, 3 test values of $z_0$ were compared with several calculated values of $z_0$ for feeder circuits involving the same kind of cable but with various assumed conditions of the return path. The calculations of $z_0$ made use of the experimentally determined "internal" self-impedance data on figure 4, in accordance with the method outlined in appendix II of a forthcoming report of the Joint Subcommittee on Development and Research, Edison Electric Institute and Bell Telephone System.[9] The comparison is presented in table I.

Although the data of table I do not permit of the absolute determination of the ground return path corresponding to any of the test conditions, they do indicate, between fairly close limits, an approximately equivalent return for circuit lengths of from 22,000 to 47,000 feet. The 2 limiting sets of circuit conditions referred to are the assumptions used in computing the zero sequence impedances of circuits 7 and 8. The moduli of the vector expressions of $z_0$ in these 2 cases, it may be noted, are not only of the same order of magnitude as those of the 3 field determinations, but their angular positions are such that they include within their phase difference of 9.5 degrees the angular positions of the 3 experimentally determined vectors (circuits 1, 2, and 3). The equivalent ground return, therefore, would consist of at least 1, and possibly 2, sheaths of similar cables in parallel with the sheath of the faulted cable, and, as implied by the separations in the limiting assumptions, the paralleling sheath, or sheaths, would run in the same duct bank as the faulted cable. The calculations also indicate the extent to which the sheath of the faulted cable serves as a return path for the current. In a system of this kind, where about half the current returns on the feeder's own

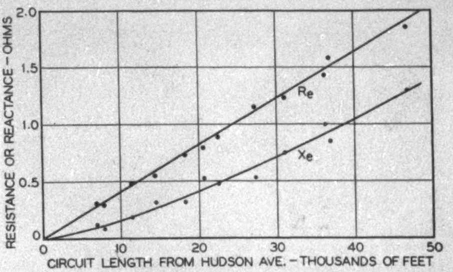

Fig. 7. Calculated "external" impedances at 60 cycles of 350,000-circular mil 3-conductor feeder circuits

**Table I—Comparison of Test and Calculated Values of Zero Sequence Impedance**

| Circuit | $r_0+j\,x_0$ Ohm per Phase per 1,000 Feet | | Current Distribution, Amperes: Faulted Cable Sheath | | Adjacent Sheaths | | Earth | |
|---|---|---|---|---|---|---|---|---|
| **Test Values** | | | | | | | | |
| 1. Test lengths 7 + 11 (22,490 feet) | 0.203 | $\underline{/44.5^\circ}$ | | | | | | |
| 2. Test lengths 7 + 11 + 12 (31,000 feet) | 0.210 | $\underline{/46^\circ}$ | | | | | | |
| 3. Test lengths 1 + 2 + 3 + 4 + 5 (46,800 feet) | 0.218 | $\underline{/48^\circ}$ | | | | | | |
| **Calculated Values Based Upon Various Assumptions** | | | | | | | | |
| 4. All current return on sheath of faulted cable | 0.281 | $\underline{/13.5^\circ}$ | 600 | $\underline{/0^\circ}$ | | | | |
| 5. Sheath of faulted cable in parallel with earth | 0.282 | $\underline{/33^\circ}$ | 547 | $\underline{/18.5^\circ}$ | | | 192 | $\overline{\backslash 65^\circ}$ |
| 6. Faulted cable paralleled by 2 sheaths at 30 inches separation; geometric mean radius of adjacent sheaths = 3 inches | 0.266 | $\underline{/41^\circ}$ | 487 | $\underline{/29^\circ}$ | 170 | $\overline{\backslash 47.5^\circ}$ | 126 | $\overline{\backslash 62^\circ}$ |
| 7. Faulted cable paralleled by 1 sheath at 8 inches separation | 0.222 | $\underline{/41.5^\circ}$ | 381 | $\underline{/26^\circ}$ | 230 | $\overline{\backslash 15^\circ}$ | 112 | $\overline{\backslash 72^\circ}$ |
| 8. Faulted cable paralleled by 2 sheaths at 6 inches separation; geometric mean radius of adjacent sheaths = 3.6 inches | 0.204 | $\underline{/51^\circ}$ | 280 | $\underline{/31.5^\circ}$ | 356 | $\overline{\backslash 11.5^\circ}$ | 77 | $\overline{\backslash 80.5^\circ}$ |

Total current = 600 amperes $\underline{/180^\circ}$; cable—350,000-circular mil 3-conductor shielded with an outside diameter of 2,950 mils; adjacent cables assumed to be of ame size; earth resistivity taken as 100 ohms per meter cube.

sheath, the earth itself forms no vital part of the return path.

The field determinations of sequence impedances have been used to calculate the currents in ground faults that have occurred on various 27 kv feeders during a 2 year period. These short circuits included 9 phase-to-ground and 3 phase-to-phase-to-ground faults. The computed ground current for each fault was compared with the chart reading of a recording ammeter in the ground circuit at Hudson Avenue station. The average agreement was within 4 per cent.

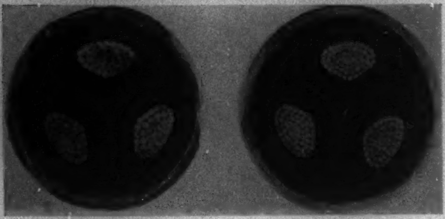
Cable *A* Cable *B*

**Fig. 8. Cross-sectional views of 2 representative makes of 27 kv 350,000-circular mil 3-conductor shielded cable in use on feeders 25-99-03 and 25-99-11**

| | Cable A | Cable B |
|---|---|---|
| Thickness of impregnated paper insulation, per conductor | 350 mils | 345 mils |
| Thickness of lead sheath | 145 mils | 150 mils |
| Outside diameter | 2,960 mils | 2,920 mils |
| Sector ratio: major axis to minor axis | 1.66 | 1.46 |
| Measured geometric mean radius of one cable conductor | 261 mils | 262 mils |
| Theoretical geometric mean radius for equivalent round conductor | 262 mils | 263 mils |
| Measured geometric mean distance between conductors | 1,275 mils | 1,288 mils |
| Theoretical geometric mean distance between conductors (see appendix I) | 1,272 mils | 1,276 mils |
| Measured-geometric mean radius of 3 conductors in one cable (see appendix II) | 751 mils | 757 mils |
| Theoretical geometric mean radius of 3 conductors in one cable | 751 mils | 754 mils |

Tests made on feeder 9950 (test length 14, figure 1) permitted a check of the method for calculating the current in a single-phase-to-ground fault. By virtue of the switching arrangement at Ainslie Street substation, it was possible to ground one phase of the feeder at that point and energize the feeder at Hudson Avenue station between this phase and ground. The impedance to the flow of current during this test was 1.60 ohms. The calculated value of this impedance, obtained by taking $^1/_3$ the sum of the measured values of positive, negative, and zero sequence impedances for the feeder, was 1.59 ohms.

### CONCLUSIONS

The specific conclusions and inferences derived from the tests have been presented as the test results themselves have been discussed. Except for the positive sequence impedance data, the results may not be generally applicable to other systems. Without the support of experimental data, it is apparent that the calculation of zero sequence impedances of feeder circuits in a system of this kind can be at best only a rough approximation. Where accurate fault calculations are required for a particular system, it would seem most advisable to conduct a series of tests on representative circuits in such manner that the data obtained could be adapted for use with all similar circuits of the system.

## Appendix I—Cable Dimensions and Discussion of Geometric Mean Distances

The several test lengths of the 350,000-circular mil 3-conductor cable included a variety of makes and ages supplied under the specification. The dimensions given in the text and in the caption for figure 6 are average values from factory cable inspection data for all makes of cable included in the feeders under observation. To illustrate typical variations in manufacture of a given type, figure 8 shows dimensions and cross-sectional views of 2 makes which represent the approximate limits in conductor sector shapes. The conductors of cable *A*, as indicated by the sector ratio, are flatter than those of cable *B*, the conductor core of which is triangular in cross section and equivalent to about 6 of the outer round strands. The "measured" geometric mean distances given in the table under figure 8 were calculated from actual measurements of strand diameters and distances between strand centers on enlargements of the photographs reproduced in the figure. The calculations were based upon assumptions of circular strand cross sections and of uniform current distribution throughout conductor sections. In making the measurements on cable *B*, each of the triangular core areas was assumed to be made up of 6 circles with diameters the same as that of the outer strands, giving cable *B* the equivalent of 60-strand conductors as compared with the 36-strand conductors of cable *A*.

The theoretical geometric mean radius of one cable conductor was calculated according to Maxwell's formula for round stranded homogeneous conductors. The theoretical geometric mean distance between conductors was obtained by the method suggested by Simmons.[8] In this method, the geometric mean distance is given by the expression $kd + 2t$, where $d$ is the diameter of the equivalent round conductor, $t$ is the conductor insulation thickness, and $k$ is the sector correction factor, which is taken between the limiting values of 0.82 and 0.86. For cable *A*, the value of $k = 0.84$ was used, and for cable *B*, $k = 0.86$.

In the absence of measured values, the "theoretical" geometric mean distances are apparently quite adequate, as their agreement with the corresponding measured distances is within 1 per cent in all instances. As Simmons already has shown, the error involved in using these spacings to calculate positive sequence reactance is negligible compared with that involved in attempting to evaluate the increase in reactance caused by the binding tapes of magnetic material. This difference is illustrated in appendix II which shows how the various test values of impedance compare with values calculated according to previously published methods.

## Appendix II—Sample Calculations of $z_1$ and $z_0$ According to Previously Published Methods

The sample calculations are for the cable described in the caption for figure 6: a 350,000-circular mil 3-conductor shielded cable, with sector conductors and steel binding tape; conductor insulation thickness, 350 mils; lead sheath thickness, 140 mils; outside diameter, 2,950 mils.

### POSITIVE SEQUENCE IMPEDANCE ($z_1$)

According to Simmons, the d-c resistance of the conductor must be increased by the following amounts:

| | |
|---|---|
| Spiraling of strands | 2.0 per cent |
| Spiraling of conductor in a 3 conductor cable | 2.0 per cent |
| Skin and proximity effects | 1.2 per cent |
| | 5.2 per cent |

To this 5.2 per cent, 1.3 per cent has been added to take into account the average excess of d-c resistance over the specified value, as indicated by factory inspection data.

$r_1$ (at 25 deg C) = 0.0308(1.065) = 0.0328 ohm per phase per 1,000 feet

$$x_1 = \frac{2\pi f}{1{,}000}\left(0.1404 \log_{10}\frac{S}{r} + 0.01525\right) \text{ ohms per phase per 1,000 feet}$$

where

$f$, the frequency = 60 cycles per second
$S$, the conductor spacing = $kd + 2t$ = 0.84(681) + 2(350) = 1,272 mils
$r$, the radius of equivalent round conductor = $\frac{681}{2}$ = 340.5 mils
$x_1$ = 0.0360 ohm per phase per 1,000 feet
Calculated value of $z_1 = 0.0328 + j0.0360$ ohm per phase per 1,000 feet
Test value at 200 amp per phase of $z_1 = 0.0334 + j0.0410$ ohm per phase per 1,000 feet

Both components of the calculated positive sequence impedance are lower than the corresponding test values, the resistance by 2 per cent and the reactance by 12 per cent. The difference between the resistance values hardly merits consideration; but the difference in reactance is large enough, when calculating positive sequence reactances of cables with steel binding tapes, to increase the theoretical reactance by an amount which, Simmons states, should be somewhere between 10 and 20 per cent, depending on the quality and quantity of the steel.

### Zero Sequence Impedance ($z_0$)

Where the sheath is assumed to be well grounded and the cable of long length, so that maximum return current in the earth will be obtained, Wagner and Evans[4] consider the equivalent circuit to consist of the impedance of the 3 paralleled cable conductors in series with the impedance formed by paralleling the sheath resistance with the mutual impedance between the sheath and the 3 cable conductors:

$$\text{Conductor resistance at 25 deg C} = \frac{r_1}{3} = \frac{0.0328}{3} = 0.0109 \text{ ohm per 1,000 feet} \quad (1)$$

$$\text{Conductor reactance} = \frac{0.004657}{5.28} f \log_{10} \frac{\text{G.M.D., conductor to sheath}}{\text{G.M.R. of 3 conductors in one cable}} \text{ ohms per 1,000 feet} \quad (2)$$

G.M.D (geometric mean distance) conductor to sheath = $\frac{r_4 + r_5}{2}$, approximately

$r_4$ = inside radius of sheath in mils
$r_5$ = outside radius of sheath in mils

$$\text{G.M.D., conductor to sheath} = \frac{1{,}335 + 1{,}475}{2} = 1{,}405 \text{ mils}$$

G.M.R. (geometric mean radius) of 3 conductors in one cable =

$$\sqrt[3]{(\text{G.M.R. of one conductor})(\text{G.M.D. between conductors})^2} = \sqrt[3]{(0.768)(340.5)(1{,}272)^2} = 751 \text{ mils}$$

$$\text{Conductor reactance} = \frac{0.004657}{5.28} 60 \log_{10}\frac{1{,}405}{751} = 0.0144 \text{ ohm per 1,000 feet}$$

$$\text{Sheath resistance} = \frac{7936\, s\, (10)^6}{(r_5^2 - r_4^2)5.28} \text{ ohms per 1,000 feet} \quad (3)$$

$s$, the lead resistivity = $22.1(10)^{-6}$ ohm per centimeter cube at 20 deg C
$r_4$ = inside radius of sheath = 1,335 mils
$r_5$ = outside radius of sheath = 1,475 mils

$$\text{Sheath resistance at 20 deg C} = \frac{1{,}503(22.1)}{(1{,}475)^2 - (1{,}335)^2} = 0.0844 \text{ ohm per 1,000 feet}$$

$$\text{Mutual resistance} = \frac{0.00159}{5.28} f = 0.0181 \text{ ohm per 1,000 feet} \quad (4)$$

$$\text{Mutual reactance} = \frac{0.004657}{5.28} f \log_{10} \frac{D_e(12{,}000)}{\text{G.M.D., conductor to sheath}} \text{ ohms per 1,000 feet} \quad (5)$$

$D_e$, equivalent depth of earth return = 2,800 feet at 60 cycles when earth resistivity is taken as 100 ohms per meter cube

$$\text{Mutual reactance} = \frac{0.004657}{5.28} 60 \log_{10} \frac{2{,}800(12{,}000)}{1{,}405} = 0.232 \text{ ohms per 1,000 feet}$$

$$z_0 = 3\left[\frac{0.0844(0.0181 + j\,0.232)}{0.0844 + 0.0181 + j\,0.232} + 0.0109 + j\,0.0144\right]$$

$$= 0.253 + j\,0.121 \text{ ohm per phase per 1,000 feet}$$

or

$$z_0 = 7.5\, r_1 + j\, 2.9 x_1$$

For a total current of 600 amperes under these conditions, the distribution between sheath and earth would result in having the sheath carry 550 $\underline{/19.5^\circ}$ amperes, and the earth 200 $\overline{\backslash 66^\circ}$ amperes. (Compare with computation 5 in table I.)

### Earth Resistivity ($\rho$)

To illustrate the effect of changes in earth resistivity on the calculated value of zero sequence impedance and on the return current distribution, the case in which the faulted cable was assumed to be paralleled by one sheath at a spacing of 8 inches (computation 2 in table I) was recomputed for 2 additional values of $\rho$, with the following results:

| $\rho$ Ohms per Meter Cube | $r_0 + jx_0$ Ohm per Phase per 1,000 Feet | Current Distribution, Amperes: Faulted Cable Sheath | Adjacent Sheath | Earth |
|---|---|---|---|---|
| 10 | $0.159 + j\,0.240$ | 376 $\underline{/26^\circ}$ | 220 $\overline{\backslash 13^\circ}$ | 128 $\overline{\backslash 61.5^\circ}$ |
| 100 | $0.166 + j\,0.147$ | 381 $\underline{/26^\circ}$ | 230 $\overline{\backslash 15^\circ}$ | 112 $\overline{\backslash 72^\circ}$ |
| 1,000 | $0.169 + j\,0.102$ | 382 $\underline{/25^\circ}$ | 230 $\overline{\backslash 16.5^\circ}$ | 102 $\overline{\backslash 70.5^\circ}$ |

Between the foregoing limits of $\rho$, which are the resistivities for swampy ground and dry earth, respectively, the absolute value of $z_0$ undergoes a change of approximately 30 per cent; but it may be noted that the distribution of the return current, for practical purposes of fault calculation, remains about the same.

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# Equivalent Circuits—
# 2 Coupled Circuits

**An equivalent circuit to represent 2 coupled circuits having distributed self- and mutual impedance and admittance is developed in this paper for the general case, and modified for certain specific cases. The application of these equivalent circuits for representation of coupled power circuits or a coupled power circuit and ground wire or metallic cable sheath with distributed grounding impedance in power system analysis is discussed.**

By
**J. C. BALSBAUGH**
MEMBER A.I.E.E.

**R. B. GOW***
ASSOCIATE A.I.E.E.

**W. P. DOUGLASS***
Membership Application Pending

**A. H. LEAL***
ENROLLED STUDENT

All of Massachusetts Institute of Technology, Cambridge

THE USE of equivalent circuits generally aids and simplifies the analysis of steady state or transient conditions in electric power systems. An equivalent circuit is developed generally to represent terminal conditions. In many cases internal conditions may be conveniently obtained from the terminal conditions and the constants of the equivalent circuit. For 3 phase balanced systems the equivalent circuits are generally developed on a per phase basis to represent positive, negative, or zero sequence components. Equivalent circuits consisting of definite impedances or admittance links may be conveniently set up on a network analyzer, thereby permitting measurement of quantities to be made directly instead of through laborious calculation involving the general circuit equations.

The present problem involves the development of an equivalent circuit to represent 2 coupled circuits (figure 1) having uniformly distributed self- and mutual impedance and admittance. These circuits may have different values of self-impedance and admittance per unit length and are not connected to busses at either end. Thus the most general case is represented. For the 3 phase case it is assumed that these circuits represent a balanced system having equal impedances and admittances per phase. These 2 circuits may represent 2 coupled power circuits to either positive, negative, or zero sequence current and voltage components, or may represent a power circuit and a ground wire or cable sheath to zero sequence components.

Starr[1] has developed equivalent circuits for an electromagnetically coupled multiple circuit line, these circuits being connected to a bus at one end. These equivalent circuits find an extensive application where the self- and mutual admittances of the circuits properly may be neglected. There are many instances, however, in which the effects of the self- and mutual admittances may be quite significant. Examples of these are: relatively long high-voltage overhead multiple circuit transmission lines; ground wires having relatively high tower grounding resistances (the ground wire with tower grounding resistances expressed in terms of the equivalent smooth line); high voltage underground cable circuits; and metallic sheath circuits with grounding resistance or impedance (the sheath circuit with grounding resistance or impedance expressed in terms of the equivalent smooth line). The effect on ground faults of the self- and mutual admittance and of ground wire and cable sheath grounding impedance may be quite important in determining the values of breaker interrupting duties, in determining phase and magnitude of currents and voltages actuating relays, and in stability studies.

The positive and negative sequence mutual impedance and admittance between multiple circuit power lines is usually relatively small in comparison to the corresponding self-impedance and admittance. Accordingly, where it is desired to include shunt capacitance effects in the analysis or representation of these circuits to positive and negative sequence components, this may be approximated by using the equivalent Π or T circuit for the individual smooth line. However, the zero sequence mutual impedance and admittance between multiple circuit power lines or between power lines and ground wires or cable sheaths is usually quite significant in comparison to the zero sequence self-impedance and admittance per circuit. Accordingly it is frequently necessary to include the coupling effect between

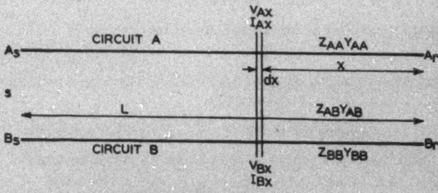

**Fig. 1. Diagram showing general relations in 2 coupled circuits**

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* Formerly graduate students, Massachusetts Institute of Technology; present affiliations: W. P. Douglass, The Proctor and Gamble Company, Ivorydale, Ohio; R. B. Gow, Kansas Gas and Electric Company, Wichita; A. H. Leal, Rio de Janeiro (Brazil, S. A.) Tramway Light and Power Company, Ltd.

[1] For numbered references see list at end of paper.

multiple circuit lines for analysis or representation of the circuits to zero sequence components. Other examples of importance are ground wires with appreciable tower grounding resistances and cable sheaths with appreciable grounding resistances or impedances as shown diagrammatically in figure 2. Assume that the top circuit of figure 2 represents a ground wire with zero sequence self-impedance $z_{s0}$ per phase per unit length of line and with equal and uniformly spaced zero sequence grounding impedance $z_{g0}$ per phase. This circuit may be changed to the middle circuit shown in figure 2 by representing $z_{g0}$ by 2 impedances in parallel, each impedance being $2z_{g0}$. Now the Π circuits, having series impedances equal to $z_{s0}$ times the units of line length between grounding points and having shunt admittances equal to $^{1}/_{2}z_{g0}$ may be changed into a smooth line (figure 2, bottom) having uniformly distributed zero sequence self-impedance and admittance $z_0$ and $y_0$, respectively, per unit length and with terminal grounding impedance equal to $2z_{g0}$. The capacitance of the circuit to ground may be in $y_0$ if desired.

The equivalent circuit shown in figure 3 represents the general case of 2 circuits with uniformly distributed self- and mutual impedance and admittance, and with the circuits not connected to busses at either end. Thus this equivalent circuit will represent terminal conditions for a double circuit power line to any sequence components or will represent terminal conditions of a power circuit and ground wire with tower grounding resistance or a power circuit and cable sheath with grounding resistances to zero sequence components. The circuit representing the ground wire may represent more than one ground wire where the ground wires may be properly combined into an equivalent ground wire. The foregoing is also true for the case of sheath representation as between single and 3 conductor cables.

For the condition of the circuits connected to a bus at one end, the 5 terminal network of figure 3 may be reduced to a 4 terminal network and the number of links reduced from 10 to 6. However, even in this case it is usually desirable to use the equivalent circuit of figure 3 to retain the identity of the line currents at the connecting point and thereby permit direct measurement of these quantities. For a double circuit power line the connecting point may be either a high or low voltage bus and for a power line and ground wire or cable sheath, the connecting point may be the common neutral point for the case of the terminal line equipment permitting the flow of zero sequence currents. In these cases the impedance of the terminal equipment must be included in the equivalent circuit at the proper places. This equivalent circuit is of course also applicable to circuit representation in an ungrounded system since in this case the path of zero sequence current on ground faults is through the circuit shunt admittance.

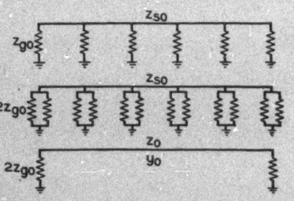

**Fig. 2. Diagrams of circuit with distributed grounding impedances**

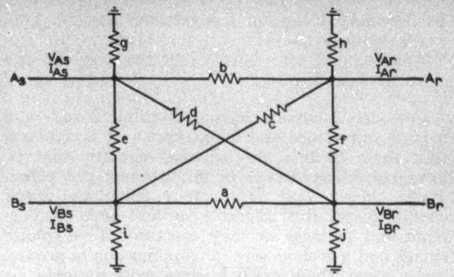

**Fig. 3. Equivalent circuit representing the general case of 2 circuits not connected to busses and having uniformly distributed self- and mutual impedance and admittance**

For the condition of a double circuit power line connected to a bus at one end and consisting of circuits having equal self-impedances and admittances, the equivalent circuit of figure 3 may be reduced to that shown in figure 4. With these circuits connected to busses at both ends the equivalent circuit of figure 4 reduces to the Π circuit shown in figure 5.

In some instances it may be desirable to include the effect of distributed grounding resistance of cable sheaths or ground wire circuits but to neglect the effect of the power circuit self-admittance and the mutual admittance. Such an instance might arise from the length of circuit involved, potential of power circuit, or simply from a desire to investigate the separate effects of distributed grounding impedance and of capacitance. The equivalent circuit to represent this case is given in figure 6. It differs from the general case of figure 3 in that $Y_{AA} = Y_{AB} = 0$. Thus the equivalent circuit of figure 6 may be used to represent to zero sequence components a single circuit power line (circuit *A*) and a ground wire or cable sheath (circuit *B*) in which the distributed ground impedances are included and capacitances are neglected.

For the condition of the distributed grounding impedances equal to zero, the equivalent circuit of figure 6 reduces to the single impedance link *a* with the value given in equations 22. For the condition of the distributed ground impedances equal to infinity, the equivalent circuit of figure 6 reduces to the equivalent circuit of figure 7, and is similar to the general equivalent circuit of a 2 circuit transformer as given by Campbell.[2] This equivalent circuit may be used for a double circuit power line in which capacitances are neglected.

## I—GENERAL CASE OF 2 CIRCUITS HAVING DISTRIBUTED SELF- AND MUTUAL IMPEDANCE AND ADMITTANCE, AND NOT CONNECTED TO BUSSES AT EITHER END

Consider 2 circuits having distributed self- and mutual impedance and admittance. It is assumed that these circuits are balanced circuits, that is, have equal impedances or admittances per phase. These circuits may represent 2 polyphase power circuits to positive, negative, or zero sequence currents and voltages or may represent a polyphase circuit and a ground wire (or combination of ground wires where these ground wires may properly be represented by an equivalent ground wire) to zero sequence currents and voltages.

The parameters of these circuits are shown in figure 1. At a distance $x$ measured from the receiving end, the following differential equations may be established:

$$\left.\begin{aligned}
\frac{dV_{Ax}}{dx} &= Z_{AA}I_{Ax} + Z_{AB}I_{Bx}\\
\frac{dV_{Bx}}{dx} &= Z_{BB}I_{Bx} + Z_{AB}I_{Ax}\\
\frac{dI_{Ax}}{dx} &= Y_{AA}V_{Ax} + Y_{AB}V_{Bx}\\
\frac{dI_{Bx}}{dx} &= Y_{BB}V_{Bx} + Y_{AB}V_{Ax}
\end{aligned}\right\}\quad(1)$$

Differentiating and rearranging gives

$$\left.\begin{aligned}
\frac{d^2V_{Ax}}{dx^2} &= K_aV_{Ax} + K_bV_{Bx}\\
\frac{d^2V_{Bx}}{dx^2} &= K_cV_{Ax} + K_dV_{Bx}\\
\frac{d^2I_{Ax}}{dx^2} &= K_aI_{Ax} + K_cI_{Bx}\\
\frac{d^2I_{Bx}}{dx^2} &= K_bI_{ax} + K_dI_{Bx}
\end{aligned}\right\}\quad(2)$$

in which

$$\left.\begin{aligned}
K_a &= Z_{AA}Y_{BB} + Z_{AB}Y_{AB}\\
K_b &= Z_{AB}Y_{BB} + Z_{AA}Y_{AB}\\
K_c &= Z_{AB}Y_{AA} + Z_{BB}Y_{AB}\\
K_d &= Z_{BB}Y_{BB} + Z_{AB}Y_{AB}
\end{aligned}\right\}\quad(3)$$

The solutions of equations 2 may be written as follows:

$$\left.\begin{aligned}
V_{Ax} &= C_a\epsilon^{p_ax} + C_b\epsilon^{p_bx} + C_c\epsilon^{p_cx} + C_d\epsilon^{p_dx}\\
V_{Bx} &= D_aC_a\epsilon^{p_ax} + D_aC_b\epsilon^{p_bx} + D_bC_c\epsilon^{p_cx} + D_bC_d\epsilon^{p_dx}\\
I_{Ax} &= M_a\epsilon^{p_ax} + M_b\epsilon^{p_bx} + M_c\epsilon^{p_cx} + M_d\epsilon^{p_dx}\\
I_{Bx} &= N_aM_a\epsilon^{p_ax} + N_aM_b\epsilon^{p_bx} + N_bM_c\epsilon^{p_cx} + N_bM_d\epsilon^{p_dx}
\end{aligned}\right\}\quad(4)$$

in which

$$\left.\begin{aligned}
p_a &= \sqrt{\frac{1}{2}\left[K_d + K_a + \sqrt{(K_d - K_a)^2 + 4K_bK_c}\right]}\\
p_b &= -p_a\\
p_c &= \sqrt{\frac{1}{2}\left[K_d + K_a - \sqrt{(K_d - K_a)^2 + 4K_bK_c}\right]}\\
p_d &= -p_c
\end{aligned}\right\}\quad(5)$$

and

$$\left.\begin{aligned}
D_a &= -\frac{2K_c}{K_d - K_a - \sqrt{(K_d - K_a)^2 + 4K_bK_c}}\\
D_b &= -\frac{2K_c}{K_d - K_a + \sqrt{(K_d - K_a)^2 + 4K_bK_c}}\\
N_a &= -\frac{2K_b}{K_d - K_a - \sqrt{(K_d - K_a)^2 + 4K_bK_c}}\\
N_b &= -\frac{2K_b}{K_d - K_a + \sqrt{(K_d - K_a)^2 + 4K_bK_c}}
\end{aligned}\right\}\quad(6)$$

Evaluating the remaining coefficients of equations 4 from known terminal conditions will permit writing equations 4 in terms of terminal voltages and currents of circuits $A$ and $B$. This gives

$$\left.\begin{aligned}
V_{As} = \frac{1}{D_a - D_b}&[(V_{Br} - D_bV_{Ar})\cosh\theta_a + (I_{Ar}Z_a +\\
&I_{Br}Z_b)\sinh\theta_a - (V_{Br} - D_aV_{Ar})\cosh\theta_b -\\
&\qquad(I_{Ar}Z_c + I_{Br}Z_d)\sinh\theta_b]\\
V_{Bs} = \frac{1}{D_a - D_b}&[D_a(V_{Br} - D_bV_{Ar})\cosh\theta_a +\\
&D_a(I_{Ar}Z_a + I_{Br}Z_b)\sinh\theta_a - D_b(V_{Br} -\\
&\qquad D_aV_{Ar})\cosh\theta_b - D_b(I_{Ar}Z_c + I_{Br}Z_d)\sinh\theta_b]\\
I_{As} = \frac{1}{N_a - N_b}&[(I_{Br} - N_bI_{Ar})\cosh\theta_a + (V_{Ar}Y_a +\\
&V_{Br}Y_b)\sinh\theta_a - (I_{Br} - N_aI_{Ar})\cosh\theta_b -\\
&\qquad(V_{Ar}Y_c + V_{Br}Y_d)\sinh\theta_b]\\
I_{Bs} = \frac{1}{N_a - N_b}&[N_a(I_{Br} - N_bI_{Ar})\cosh\theta_a +\\
&N_a(V_{Ar}Y_a + V_{Br}Y_b)\sinh\theta_a - N_b(I_{Br} -\\
&\qquad N_aI_{Ar})\cosh\theta_b - N_b(V_{Ar}Y_c + V_{Br}Y_d)\sinh\theta_b]
\end{aligned}\right\}\quad(7)$$

in which

$$\left.\begin{aligned}
Z_a &= \frac{(Z_{AB} - D_bZ_{AA})L}{\theta_a}\\
Z_b &= \frac{(Z_{BB} - D_bZ_{AB})L}{\theta_a}\\
Z_c &= \frac{(Z_{AB} - D_aZ_{AA})L}{\theta_b}\\
Z_d &= \frac{(Z_{BB} - D_aZ_{AB})L}{\theta_b}
\end{aligned}\right\}\quad(8)$$

$$\left.\begin{aligned}
Y_a &= \frac{(Y_{AB} - N_bY_{AA})L}{\theta_a}\\
Y_b &= \frac{(Y_{BB} - N_bY_{AB})L}{\theta_a}\\
Y_c &= \frac{(Y_{AB} - N_aY_{AA})L}{\theta_b}\\
Y_d &= \frac{(Y_{BB} - N_aY_{AB})L}{\theta_b}
\end{aligned}\right\}\quad(9)$$

and

$$\left.\begin{aligned}
\theta_a &= p_aL\\
\theta_b &= p_cL
\end{aligned}\right\}\quad(10)$$

The equivalent circuit to represent the coupled circuits of figure 2 between terminals may be determined from equations 7. Since there are 5 terminals the equivalent circuit of figure 2 will contain a minimum of 10 links. The links of this equivalent circuit may be evaluated by applying successively unit voltage to each of the circuit terminals, the remaining terminals being grounded, and then setting up and solving equations defining the relations between terminal voltages and currents from the equivalent circuit and from equations 7. This gives the impedance links $a$ to $j$ inclusive of figure 3 by

$$\left.\begin{aligned}
a &= \frac{(Z_aZ_d - Z_bZ_c)\sinh\theta_a\sinh\theta_b}{Z_a\sinh\theta_a - Z_c\sinh\theta_b}\\
b &= \frac{(Z_aZ_d - Z_bZ_c)\sinh\theta_a\sinh\theta_b}{D_aZ_b\sinh\theta_a - D_bZ_d\sinh\theta_b}\\
c = d &= \frac{(Z_aZ_d - Z_bZ_c)\sinh\theta_a\sinh\theta_b}{Z_d\sinh\theta_b - Z_b\sinh\theta_a}\\
\frac{1}{e} = \frac{1}{f} &= \frac{Z_b}{(Z_aZ_d - Z_bZ_c)\tanh\theta_b} - \frac{Z_d}{(Z_aZ_d - Z_bZ_c)\tanh\theta_a}\\
\frac{1}{g} = \frac{1}{h} &= \frac{(1 - D_b)Z_d\tanh\theta_a/2 - (1 - D_a)Z_b\tanh\theta_b/2}{Z_aZ_d - Z_bZ_c}\\
\frac{1}{i} = \frac{1}{j} &= \frac{(1 - D_a)Z_a\tanh\theta_b/2 - (1 - D_b)Z_c\tanh\theta_a/2}{Z_aZ_d - Z_bZ_c}
\end{aligned}\right\}\quad(11)$$

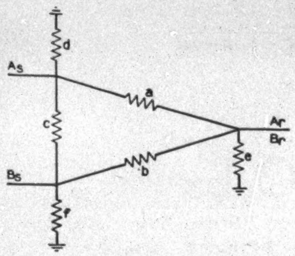

**Fig. 4. Equivalent circuit derived from figure 3 by connecting circuits to a bus at one end**

## II. Case of 2 Circuits Having Distributed and Equal Self- and Mutual Impedance and Admittance, and Not Connected to Busses at Either End

This represents a particular instance under case I. It is applicable to a multiple circuit power line consisting of similar circuits and may represent this case to positive, negative, or zero sequence currents and voltages. For this the circuit parameters may be represented by

$$\left.\begin{aligned}
Z_s &= Z_{AA} = Z_{BB}\\
Z_m &= Z_{AB}\\
Y_s &= Y_{AA} = Y_{BB}\\
Y_m &= Y_{AB}
\end{aligned}\right\}\quad(12)$$

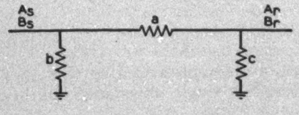

**Fig. 5. Equivalent circuit derived from figure 3 by connecting circuits to busses at both ends**

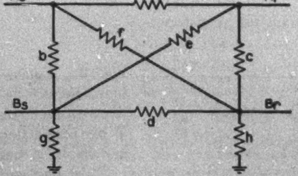

**Fig. 6. Equivalent circuit differing from figure 3 in that self-admittance and mutual admittance of one circuit are zero**

Substituting these values in equations 3, 5, 6, 8, 9, and 10 gives

$$\left.\begin{aligned}
K_a &= K_d = Z_sY_s + Z_mY_m\\
K_b &= K_c = Z_sY_m + Z_mY_s
\end{aligned}\right\}\quad(13)$$

$$\left.\begin{aligned}
p_a &= \sqrt{(Z_s + Z_m)(Y_s + Y_m)}\\
p_b &= \sqrt{(Z_s - Z_m)(Y_s - Y_m)}
\end{aligned}\right\}\quad(14)$$

$$\left.\begin{aligned}
D_a &= N_a = 1\\
D_b &= N_b = -1
\end{aligned}\right\}\quad(15)$$

$$\left.\begin{aligned}
Z_a &= Z_b = \sqrt{\frac{Z_s + Z_m}{Y_s + Y_m}} = \frac{1}{Y_a} = \frac{1}{Y_b}\\
Z_d &= -Z_c = \sqrt{\frac{Z_s - Z_m}{Y_s - Y_m}} = \frac{1}{Y_d} = -\frac{1}{Y_c}
\end{aligned}\right\}\quad(16)$$

$$\left.\begin{aligned}
\theta_a &= p_aL\\
\theta_b &= p_bL
\end{aligned}\right\}\quad(17)$$

Substituting the foregoing in equations 7 gives

$$\left.\begin{aligned}
V_{As} &= \frac{(V_{Ar} + V_{Br})}{2}\cosh\theta_a + \frac{(I_{Ar} + I_{Br})}{2}Z_a\sinh\theta_a\\
&\quad + \frac{(V_{Ar} - V_{Br})}{2}\cosh\theta_b + \frac{(I_{Ar} - I_{Br})}{2}Z_d\sinh\theta_b\\
I_{As} &= \frac{(I_{Ar} + I_{Br})}{2}\cosh\theta_a + \frac{(V_{Ar} + V_{Br})}{2Z_a}\sinh\theta_a\\
&\quad + \frac{(I_{Ar} - I_{Br})}{2}\cosh\theta_b + \frac{(V_{Ar} - V_{Br})}{2Z_d}\sinh\theta_b
\end{aligned}\right\}\quad(18)$$

and $V_{Bs}$ and $I_{Bs}$ in terms of $V_{Ar}$, $V_{Br}$, $I_{Ar}$ and $I_{Br}$ may be obtained from these equations by interchanging subscripts $A$ and $B$.

The impedance links of the equivalent circuit representing this instance may be determined similarly as for case I or may be determined from equations 11. The equivalent circuit may be represented by figure 3 in which the impedance links are

$$\left.\begin{aligned}
a = b &= \frac{2Z_aZ_d\sinh\theta_a\sinh\theta_b}{Z_a\sinh\theta_a + Z_d\sinh\theta_b}\\
c = d &= \frac{2Z_aZ_d\sinh\theta_a\sinh\theta_b}{Z_d\sinh\theta_b - Z_a\sinh\theta_a}\\
\frac{1}{e} = \frac{1}{f} &= \frac{1}{2Z_d\tanh\theta_b} - \frac{1}{2Z_a\tanh\theta_a}\\
\frac{1}{g} = \frac{1}{h} = \frac{1}{i} = \frac{1}{j} &= \frac{\tanh\theta_a/2}{Z_a}
\end{aligned}\right\}\quad(19)$$

In connection with the development of the foregoing equivalent circuits as given in this and the preceding section, it may be interesting to compare equations 7 and 18 relating terminal voltages and currents for the double circuit line with those for the single circuit smooth line.

## III. CASE OF 2 CIRCUITS HAVING DISTRIBUTED AND EQUAL SELF- AND MUTUAL IMPEDANCE AND ADMITTANCE, AND CONNECTED TO BUSSES

For the case of the circuits connected to a bus at one or both ends the number of terminals of the network will be reduced and accordingly the number of links may be reduced. However, reducing the network may prevent the line currents at the connecting points from being measured directly. The equivalent circuits of figure 3 may be used with the appropriate terminals connected together.

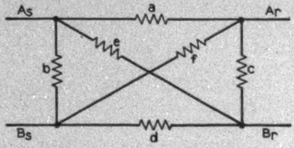

**Fig. 7. Equivalent circuit derived from figure 6 by making the distributed ground impedances infinite**

For the condition of similar circuits connected at one end the equivalent circuit of figure 3 reduces to that shown in figure 4. The equivalent circuit of figure 4 with impedance and admittance links given in series form was first given by Wagner and Evans.[3] The links of figure 4 are

$$\left.\begin{aligned}
a &= b = Z_a \sinh \theta_a = \frac{(Z_s + Z_m)\sinh \theta_a}{\theta_a}\\
\frac{1}{c} &= \frac{1}{2Z_d \tanh \theta_b} - \frac{1}{2Z_a \tanh \theta_a}\\
\frac{1}{d} &= \frac{1}{f} = \frac{1}{2e} = \frac{\tanh \theta_a/2}{Z_a} = (Y_s + Y_m)\frac{\tanh \theta_a/2}{\theta_a}
\end{aligned}\right\} \quad (20)$$

and $Z_s$, $Z_m$, $Y_s$, $Y_m$, $Z_a$, $Z_b$ and $\theta_a$, $\theta_b$, are given by equations 12, 14, 16, and 17.

For the condition of 2 similar lines connected to busses at both ends the equivalent circuit of figure 4 reduces to the 3 terminal network of figure 5 with the links of the equivalent circuit given by

$$\left.\begin{aligned}
a &= \frac{Z_a}{2}\sinh \theta_a = \frac{(Z_s + Z_m)}{2}\,\frac{\sinh \theta_a}{\theta_a}\\
\frac{1}{b} &= \frac{1}{c} = \frac{2\tanh \theta_a/2}{Z_a} = 2(Y_s + Y_m)\frac{\tanh \theta_a/2}{\theta_a}
\end{aligned}\right\} \quad (21)$$

and $Z_s$, $Z_m$, $Y_s$, $Y_m$, $Z_a$, $\theta_a$ are given by equations 12, 14, 16, and 17.

## IV. GENERAL CASE WITH SELF-ADMITTANCE OF ONE CIRCUIT AND MUTUAL ADMITTANCE BETWEEN CIRCUITS EQUAL TO ZERO

This special instance of case I has particular application for representing a single circuit line and ground wire or cable sheath to zero sequence components for the condition of including distributed grounding resistance or impedance and neglecting the effect of capacitance. The equivalent circuit of figure 3 may be reduced to that shown in figure 6 in which the impedance links are ($Y_{AA} = Y_{AB} = 0$):

$$\left.\begin{aligned}
a &= \frac{Z_{AA}Z_{BB} - Z_{AB}^2}{Z_{BB}}\\
b &= c = \frac{Z_{AA}Z_{BB} - Z_{AB}^2}{Z_{AB}} = -e = -f\\
\frac{1}{d} &= \frac{\theta}{Z_{BB}\sinh \theta} - \frac{Z_{AB}^2}{(Z_{AB}^2 - Z_{AA}Z_{BB})Z_{BB}}\\
\frac{1}{g} &= \frac{1}{h} = \frac{\theta}{Z_{BB}}\tanh \frac{\theta}{2}\\
&\text{and}\\
\theta &= \sqrt{Z_{BB}Y_{BB}}
\end{aligned}\right\} \quad (22)$$

## V. GENERAL CASE WITH SELF-ADMITTANCE OF BOTH CIRCUITS AND MUTUAL ADMITTANCE EQUAL TO ZERO

This special instance of case I assumes that capacitance effects in the circuits are either negligible or may be neglected. Where one of the circuits represents a ground wire or cable sheath it is assumed that the grounding resistances are zero or negligible and the corresponding terminal or terminals are grounded in the equivalent circuit. The equivalent circuit for this case may be obtained from figure 6 for $Y_{22} = 0$ and gives the equivalent circuit of figure 7 in which

$$\left.\begin{aligned}
a &= \frac{Z_{AA}Z_{BB} - Z_{AB}^2}{Z_{BB}} \quad d = \frac{Z_{AA}Z_{BB} - Z_{AB}^2}{Z_{AA}}\\
b &= c = \frac{Z_{AA}Z_{BB} - Z_{AB}^2}{Z_{AB}} = -e = -f
\end{aligned}\right\} \quad (23)$$

For the condition of terminals $Ar$ and $Br$ connected the equivalent circuit of figure 7 reduces to the wye equivalent circuit[4] of figure 8, in which

$$\left.\begin{aligned}
a &= Z_{AA} - Z_{AB}\\
b &= Z_{BB} - Z_{AB}\\
c &= Z_{AB}
\end{aligned}\right\} \quad (24)$$

With the circuits connected to busses at both ends, that is $Ar$ and $Br$ connected together and $As$ and $Bs$ connected together, the equivalent circuit of figure 7 reduces to a single impedance link equal to

$$\frac{Z_{AA}Z_{BB} - Z_{AB}^2}{Z_{AA} + Z_{BB} - 2Z_{AB}} \quad (25)$$

and if similar circuits are represented so that $Z_{AA} = Z_{BB}$ then the foregoing single impedance link becomes equal to

$$\frac{Z_s + Z_m}{2} \quad (26)$$

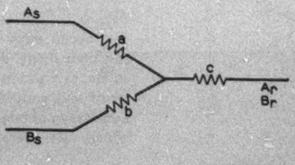

**Fig. 8. Equivalent circuit derived from figure 7 by connecting circuits to a bus at one end**

in which $Z_s$ and $Z_m$ are given by equations 12.

In connection with the foregoing, further work is planned in developing circuits covering the same conditions as described but for more than 2 coupled circuits and in determining the effects produced under system faults by the distributed self- and mutual admittance and distributed grounding impedances.

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# Overrefined Oils in Power Transformers

By
**J. G. FORD**
Member Am. Chem. Soc.
Westinghouse Elec. and Mfg. Co.,
E. Pittsburgh, Pa.

**Insulating oils ordinarily used in transformers have high stability toward oxidation, and much effort has been directed toward reducing the oxygen absorption qualities of such oils. Contrary to usual practice, however, the tests reported in this paper were made with a readily oxidizable or "overrefined" oil on the basis that the oxidizing qualities of this oil will maintain automatically an inert gas above the oil and thus reduce explosion hazards. On the basis of these tests, it is said that transformers equipped for restricted breathing can be operated with overrefined oil over long periods without servicing as far as the oil is concerned. Among the chief disadvantages of such oil is its high cost—approximately twice that of present commonly used oils.**

SINCE the invention of the oil filled transformer, the problem of oil deterioration always has been in the foreground and year after year has become more prominent, particularly because of the desire to work the insulation under increasingly higher stress and temperature. It is well known that even the best insulating oils under conditions of service gradually deteriorate, with the formation of organic acids and sludge which are detrimental and which, to a certain extent, limit the life of the transformer. While the quality of transformer oil gradually has been improved to meet requirements, nevertheless there is still much to be desired in the way of better insulating oils.

It is the purpose of this paper to show how deterioration of insulating oil can be reduced to such an extent as to minimize the maintenance problem of the operating engineer. Contrary to present practice, it is shown that by the use of a highly refined readily oxidizable oil, it is possible—under the proper conditions—to obtain extremely long life and at the same time reduce the explosion hazard by maintaining automatically an inert gas above the oil.

The composition of insulating oils for transformers will be discussed only briefly, since numerous papers have dealt with this subject in the past. The insulating oil fraction in the refining process is generally a close-cut fraction taken after the kerosene distillate and is composed of paraffin, naphthene, and perhaps some aromatic hydrocarbons, together with traces of residual petroleum resins and sulphur compounds. The proportions of these compounds will be dependent upon the type of crude, and upon the method and degree of refinement. By very drastic refining, such as using fuming sulphuric acid as the refining agent, extremely highly refined oils can be obtained; because of their peculiar behavior toward oxidation, these sometimes are called "overrefined" oils. These oils are the basis of the present paper. Although the cost is generally about twice that of conventional oils, it is believed to be justified in view of improvements shown in the following discussion. In general, if one begins with the crude distillate and progressively removes the so-called unstable constituents, the oil becomes better from the standpoint of acid and sludge developed under service conditions. However, with increased refining, an optimum is reached beyond which the oil is more susceptible to oxidation and, under some conditions, deteriorates very rapidly.[1,2,3] Experiments conducted by the author and his associates, which have been confirmed by others, indicate that this change in character of the oxidation is attributable to complete

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[1] For all numbered references, see list at end of paper.

removal of naturally occurring residual petroleum resins which act as retarders to oxidation.

Considerable study in the refining and testing of transformer oils has led to the conclusion that the problem resolves itself into an economic one. By increased cost of refining, the sludging tendency of the oil can be reduced to the point where an overrefined oil is obtained. The view sometimes is held that certainly there must exist in some types of crude oil a hydrocarbon or group of hydrocarbons that have extreme stability toward oxidation, and if such compounds could be isolated, one would have the ideal transformer oil. While this might be possible, the author's experience has indicated that it is hardly probable, and at least the cost of obtaining such compounds would be high as compared with present oil. Sometime in the future very stable materials may be obtained by synthesis, or suitable oxidation retarders may be found which can be added to the oil; but this is a matter of speculation.

Certain choice of crude, together with improved methods of refining and more experience in the service behavior of oils, have resulted in a more satisfactory product than was available in the past. While this is true, none of the present methods of refining is believed to be capable of giving the ideal oil that has been the operating engineer's hope. At some future time, radical changes in refining processes might result in better products with high resistance to oxidation, and perhaps the ideal oil will be approached.

It has long been known that insulating oil does not deteriorate if an inert gas is maintained above it. This has resulted in designing transformers with devices to remove the oxygen from the inbreathed air or to supply directly an inert gas, such as nitrogen or carbon dioxide, to the gas space. While the oil is protected in such devices, periodic inspection is necessary to guarantee proper functioning of the apparatus.

In studies on the oxidation of insulating oils, the writer was particularly impressed with the rate of oxygen absorption of the overrefined white oils. At the time, an attempt was being made to make an oil that had high stability toward oxidation, or low oxygen absorption. With the idea of an inert atmosphere above the oil in mind, the thought occurred of taking advantage of the high oxygen absorption rate of the oil to create an inert atmosphere. Possibly a reasonable life could be obtained for the oil if the supply of air were limited. In other words, the field of attack was reversed and instead of searching for a highly oxygen-resistant oil, experiments were directed to oils with high oxygen absorption. Tests in free breathing transformers with a moderately refined oil and an overrefined oil showed that when all factors were taken into consideration, the 2 oils were practically equivalent from a service standpoint. Knowing that the overrefined oil absorbed much larger quantities of oxygen than the moderately refined oil, the question arose: What are the relative deterioration rates when an equivalent amount of oxygen is supplied each oil?

**Table I—Relative Deterioration of Conventional and Overrefined Oils When Supplied With Same Amount of Oxygen**

| Oil | Neutralization* Number | Sediment Per Cent by Volume | Saponification** Number |
|---|---|---|---|
| Conventional | 0.24 | 0.84 | 2.13 |
| Overrefined | 0.15 | Trace | 2.0 |

* Milligrams of potassium hydroxide required to neutralize 1 gram of oil.
** Milligrams of potassium hydroxide required to saponify 1 gram of oil.

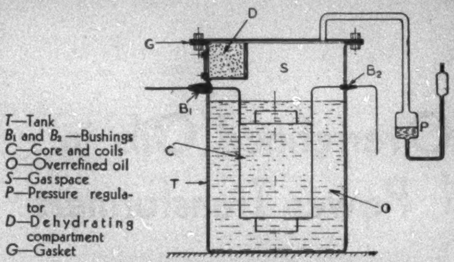

Fig. 1. Arrangement of transformer and test equipment for experiments of table III

To answer this question, a test was set up where the oils could be studied under closely controlled conditions. A slightly elevated temperature of 115 degrees centigrade was used to accelerate deterioration. The oils were placed in iron cans with gasketed steel lids. Pet cocks were installed in the covers for blowing out the gas space. The volume ratio of oil space to gas space was 4 to 1. The cans were placed in an oil bath at 115 degrees centigrade with the pet cocks closed. Once each week the gas space was blown out with air, previous tests having shown that a week at this temperature was ample time for consumption of the oxygen in the gas space. During the course of the test several oils were examined, but only typical examples will be considered here. The total oxygen consumed during the test by each sample was about 0.1 cubic foot per gallon of oil. The results of this test, given in table I, are quite interesting. They indicate the superiority of the overrefined oil when tested under these conditions. This is borne out also in the transformer tests to be discussed later.

It might be of interest to consider briefly the relative rates of oxygen absorption of the foregoing 2 oils. Samples of oil were placed in a glass bulb connected to a burette for feeding in oxygen. The oils previously were saturated with oxygen at room temperature so as to eliminate the solution error. The receptacle was heated to 125 degrees centigrade and mechanically agitated. Results are summarized briefly in table II.

It may be interesting to note that the overrefined oil as compared with the conventional oil absorbed oxygen in the ratio of 260 to 1. During the course of the oxidation, carbon dioxide and water vapor accumulated; since these were not removed, they prob-

### Table II—Relative Rates of Oxygen Absorption of Overrefined and Conventional Oils

| Oil | Temperature, Deg C | Time, Hr | Oxygen Absorbed, Cu Cm per G | Water Formed | Carbon Dioxide Formed, Cu Cm per G | Neutralization Number* of Oxidized Oil |
|---|---|---|---|---|---|---|
| Overrefined | 125 | 5 | 9.1 | 0.27% | 0.05 | 1.24 |
| Conventional | 125 | 5 | 0.035 | Trace | Trace | Trace |

* See footnote to table I.

ably had a slight influence on slowing down the rate of absorption, due to a dilution effect.

In view of the encouraging results obtained, it was thought desirable to extend the tests to transformers that could be operated under closely controlled conditions and at a temperature that would approximate service conditions. Accordingly, 3 25 kva transformers were set up with special tank construction for the experiments (see figure 1). The covers were made airtight and the gas space was connected to an oil trap with sufficient capacity to prevent the escape or intake of gas. Connections were made to the gas space for replacing the air when desired. In materials of construction, the transformers were comparable to power transformers. These transformers were operated at various temperatures with periodic checks of the oil and analysis of the gas in the gas space for oxygen. By this means it was possible to determine the approximate time necessary to reduce the oxygen to a sufficiently low concentration to prevent a gas explosion within the transformer, roughly about 4 per cent oxygen. For purposes of comparison, a conventional or moderately refined oil was used in one transformer. The other 2 transformers contained the overrefined oil, one with restricted breathing and the other with free breathing. The transformers with restricted breathing were equipped with a compartment suitable for inserting a dehydrating material to absorb the moisture from the inbreathed air and also the moisture formed as a product of oxidation. Periodically, the gas space of the restricted breathing transformer above the oil was blown out with fresh air and the rate of oxygen removal from the gas space determined by means of gas analysis. Knowing the volume of the gas space, it was possible to calculate the amount of air fed to the transformers during the tests. Table III gives a summary of the results obtained after 15 months' operation at 75 degrees centigrade.

From an inspection of table III, it may be interesting to note the large difference in rate of deterioration of the overrefined oil with restricted and with free breathing, respectively, as indicated by neutralization and saponification numbers and also by 60-cycle power-factor measurements. It also seems worth noting that the overrefined oil under restricted breathing conditions proved to be slightly better than the conventional oil under the same conditions. By comparison of the results given in tables I, II, and III, a fairly close relationship between oxygen consumed by the oil and neutralization number is indicated under the conditions of test, at least up to the present stage of deterioration, as shown by table IV.

Knowing the approximate amount of air taken into a transformer per year, assuming complete consumption of the oxygen, the degree of deterioration of the oil can be calculated roughly up to the point where the neutralization number would change as a result of sludge precipitation. Further, since there is a fairly close agreement between acidity as indicated by the neutralization number and the amount of oxygen consumed, by use of the results given in table II, it is possible to get a rough idea of the amount of water formed during the course of deterioration. From a consideration of the amount of air taken in as a result of extreme temperature changes on a transformer with restricted breathing, it is possible to calculate roughly the amount of dehydrating agent necessary to remove the water of oxidation and that contained in the inbreathed air, thus insuring high breakdown strength of the oil.

If the capacity of the overrefined type of oil as a means of creating an inert atmosphere is to be used to advantage, it is necessary to know something about the effect of temperature on the rate of absorption or consumption of the oxygen under operating conditions. Accordingly, during the transformer tests a series of runs was made to ascertain the time necessary to reduce the oxygen to a safe limit at several different temperatures. Typical results of these tests are given in figures 2 and 3. By reference to figure 2 it may be noted that at 75 degrees centigrade after 72 hours, the removal of oxygen from the gas space was practically complete with the overrefined oil, while there was still about 5 per cent oxygen present with the conventional oil; at 60 degrees, the removal of the oxygen was almost complete with the overrefined oil after 96 hours and was still about 8.5 per cent with the conventional oil; at 50 degrees, the cleanup is quite slow, but much better with the overrefined than with the conventional oil.

As indicated by the curves, the cleanup of the oxygen at the lower operating temperatures is too slow to guarantee establishment of an inert gas above the oil in a reasonably short time after breath-

### Table III—Results of Comparative Laboratory Tests on Overrefined and Conventional Oils

| | Transformer 1 | Transformer 2 | Transformer 3 |
|---|---|---|---|
| Oil | Overrefined | Overrefined | Conventional, moderately refined |
| Tank construction | Restricted breathing | Free breathing | Restricted breathing |
| Temperature, deg C | 75 | 75 | 75 |
| Oil volume, gal | 18.5 | 18.5 | 18.5 |
| Gas space, cu ft | 1.28 | 1.28 | 1.28 |
| Months of operation | 15 | 15 | 15 |
| Times blown out | 11 | Free to breathe | 11 |
| Air supplied, cu ft | 14.08 | Free to breathe | 14.08 |
| Oxygen absorbed, cu ft | 2.93 | Free to breathe | 2.93 |
| Oxygen absorbed, cu ft per gal of oil | 0.158 | Free to breathe | 0.158 |
| Neutralization number (15 months) | 0.19 | 3.97 | 0.39 |
| Saponification number (13 months) | 1.76 | 11.80 | 3.38 |
| Power factor at 60 cycles (room temperature) | 0.0034 | 0.1328 | 0.0082 |
| Sludge | Trace | Trace | Trace |

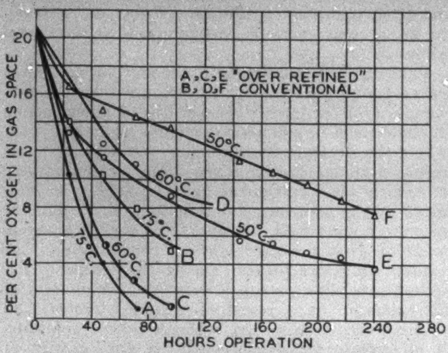

Fig. 2. Rate of oxygen absorption from gas space of transformer by conventional and overrefined oils at different temperatures

ing. Therefore, it was thought desirable to accelerate the oxygen absorption at the lower operating temperatures. Several oxidation catalysts were tried on laboratory samples of oil, particularly oil soluble metal soaps. Of the soaps tried, cobalt-manganese appeared to be the best. This is marketed under the trade name of "Soligen drier" and is used as a drier in paints, varnishes, and the like. Upon completion of the laboratory tests, a small amount of this material was added to the oil in the test transformer (about 0.002 per cent by weight) and several runs were made at 50 degrees centigrade to ascertain its influence under operating conditions. Figure 3 shows the effect of addition of this material on the rate of oxygen cleanup. It is found that at 50 degrees with the plain oil, the oxygen concentration was still 3.8 per cent after 240 hours, whereas with the catalyst present the concentration was reduced to 0.4 per cent in 96 hours and to a safe limit in 48 hours. The writer wishes to point out that the successful operation of overrefined oil in the transformer described depends largely on the restricted breathing feature. The exhaust valve is so regulated that for normal changes of temperature there is no interchange of gas with the outside atmosphere. The regulation of the valve will depend chiefly on the pressure limits of the tank, but usually is adjusted to breathe in at about 1/4 pound per square inch below atmospheric pressure and exhaust at about 5 pounds per square inch above atmospheric pressure. This means that the transformer breathes only during extreme temperature changes and that when breathing does take place, the resultant oxygen concentration generally will be too low to give an explosive mixture with oil vapors or decomposition products.

By reference to table II, it may be noted that the ratio of oxygen absorption of the overrefined oil and conventional oil was 260 to 1, whereas in the transformer tests a ratio of about 3 to 1 was obtained. The only explanation the writer can advance for this difference in the rates of absorption under the conditions of test is the possibility of the effect on oxygen concentration or solution of a small amount of gum or resin from the transformer insulation, which might act as an oxidation retarder. When new, the overrefined white oils usually are characterized by a latent period of oxidation during which time very little change takes place in the oil and oxygen absorption is very slow. The behavior during this time suggests that there is an oxidation catalyst accumulating which, when present in sufficient amounts, materially accelerates the rate of oxygen absorption. Perhaps a chain reaction is initiated at this point. The rôle of residual petroleum resins in acting as retarders in the conventional type of oil may be their ability to intercept the chain reaction in process. To insure cleanup of oxygen during the early life of the transformer, the oil can be oxidized to a degree slightly beyond the latent period. A small amount of previously oxidized oil can be added, which also will hasten the initial oxidation.

This preliminary treatment is not necessary when a catalyst is added to the oil. The catalyst can be added directly to the oil or can be applied to the tank walls of the transformer in the form of an oil soluble varnish. There are numerous materials that, when added to oil, tend to retard the rate of oxygen absorption. For the application just described, it is believed to be necessary to use extreme precaution in the choice of insulating varnishes and gums in order to guarantee rapid cleanup of oxygen from the gas space. The transformer tests herein described were made after the latent period of oxidation of the oil was passed.

Field experience on a number of power transformers with restricted breathing has shown that the average amount of air breathed in per year on a 10,000 kva transformer containing 5,000 gallons of oil is approximately 130 cubic feet. This would correspond to 0.026 cubic foot of air per gallon of oil or 0.0054 cubic foot of oxygen. By reference to table III, it is observed that when the oxygen consumption was 0.158 cubic foot per gallon, the neutralization number was 0.19, saponification number 1.76, and power factor at 60 cycles and 25 degrees centigrade was only 0.0034. Compared with the 10,000 kva transformer, this would correspond to about 29 years of service, after which the oil is found to be in very good condition with indications of an extremely long life. By reference to table III it may be observed that after admission of 14.08 cubic

Table IV—Comparison of Data in Tables I, II, and III

| Temperature of Test, Deg C | Restricted Breathing | Oxygen Consumed, Cu Ft per Gal | Oil | Neutralization Number | Neutralization Number Equivalent for 0.01 Cu Ft of Oxygen |
|---|---|---|---|---|---|
| 115 | Yes | 0.1 | Conventional | 0.24 | 0.024 |
| 115 | Yes | 0.1 | Overrefined | 0.15 | 0.015 |
| 75 | Yes | 0.158 | Conventional | 0.39 | 0.0247 |
| 75 | Yes | 0.158 | Overrefined | 0.19 | 0.012 |
| 125 | In flask with oxygen supplied | 1.025 | Overrefined | 1.24 | 0.0121 |

feet of air into a transformer containing 18.5 gallons of oil a neutralization number of 0.19 was obtained for the oil. If it be assumed that the neutralization number is proportional to the oxygen consumed, as has been indicated by tests, and that a neutralization number of 1.0 is the upper limit before conditioning is required, then approximately 20,000 cubic feet of air would be required to be breathed into a 10,000 kva transformer containing 5,000 gallons of oil before a neutralization number of 1.0 would be reached. On this assumption, with a breathing rate of 130 cubic feet of air per year, approximately 154 years would be required to attain a neutralization number of 1.0. Of course, the assumed life would decrease with increased breathing rates. Therefore, the useful life of the oil without conditioning usually would be exceptionally long except where loading might be quite variable, with resulting extreme breathing rates.

With oxidation permitted as suggested hereinbefore, through restricted breathing, it is practical to use a dehydrating material in the gas space to remove water formed from oxidation and that which enters with the inbreathed air. If the water were not removed, it would accumulate in the free state, and when dispersed in the oil would lead to low breakdown voltage. It might also collect on insulation surfaces and result in creepage paths. Here, as in the older transformers of this type, moisture is taken care of by use of a dehydrating material. By reference to table II, it may be found that with 9.1 cubic centimeters of oxygen absorbed per gram of oil, the water formed was 0.27 per cent. This is equivalent to about 18.6 pounds of water for each 1,000 cubic feet of oxygen consumed, or roughly 5,000 cubic feet of air. The amount of calcium chloride required, figuring 100 per cent excess, would be 2.2 pounds when the breathing rate is 250 cubic feet of air per year with an average outdoor temperature of 20 degrees centigrade and 60 per cent relative humidity ($CaCl_2$ to $CaCl_2.6H_2O$). It is apparent that sufficient dehydrating material can be used so that a change would be necessary only about once in 5 years. The use of a basic material, such as soda ash, along with the calcium chloride is desirable. The alkaline material combines with the low-molecular-weight organic acids formed during the oxidation. These acids are somewhat corrosive, and in solution in the oil tend to increase the power factor. Their removal therefore is desirable.

In conclusion, the writer is aware that the use of the so-called "overrefined" oils is contrary to present American practice, but it has been demonstrated that under the proper conditions of operation, this oil has very desirable properties. Indications are that with the use of the scheme proposed, a transformer can be operated over long periods without any service as far as the oil is concerned, and it appears that the oil would not have to be conditioned throughout the life of the transformer. Further, no appreciable amount of sludge would be formed to cause overheating. A service test on a 100-kva free-breathing transformer revealed that a neutralization number of 4.7 was attained before the accumulated sludge on the tank walls, core and coils, and in the ventilating ducts, caused any difficulty. The calculated life given hereinbefore is based upon a neutralization number of only 1.0. Therefore, it is apparent that sludging would not cause any trouble. Periodic inspection and changing of the dehydrating material would be necessary perhaps every 5 years. This, of course, would depend upon the breathing rate and the amount of dehydrating material used.

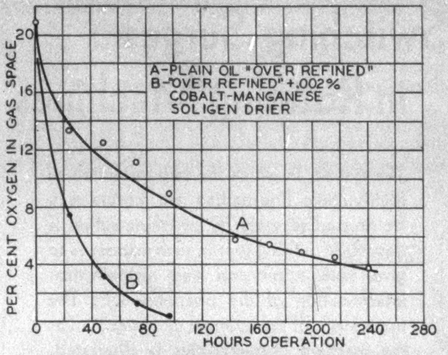

**Fig. 3. Effect of catalyst on rate of oxygen cleanup from gas space of transformer by "overrefined" oil**

The foregoing scheme has been shown to be practical and to have considerable merit in view of laboratory tests, service tests in small transformers, and, in fact, in several years' run in power transformers. However, it is believed that the commercial development should not be too rapid since experience has shown the desirability of additional work along the following lines:

1. Development of a source of cheaper oil. (The price of oil used in the above experiments is about double that of conventional oils.)
2. Further study on catalytic materials.
3. Choice of solid insulation that will not affect the rate of oxygen cleanup by the oil.

It should be pointed out also that one must be extremely careful in the choice of oil for this application, since some of the overrefined oils readily precipitate gummy deposits on oxidation. White oils have been found, however, which form largely soluble oxidation products and show far less sediment under the conditions of test than oils normally used. In order to insure rapid consumption of oxygen from the gas space, it becomes desirable to operate a transformer of this design at least 10 to 15 degrees centigrade hotter than the operating temperatures usually permitted.

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2. Die Säurebildung in Transformatorenölen, J. Marcusson and W. Bauerschafer. *Petroleum Zeitschrift*, v. 22, No. 15, May 20, 1926, p. 572–4.

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# Switching Surges in Rotating Machines

**The manner in which the turn insulation of high-voltage line-starting a-c motors may be stressed severely by switching surges is described in this paper in such manner as to give both a physical and mathematical interpretation of the phenomena. The importance of the external circuit as well as the machine characteristics is illustrated. Methods are presented for estimating the severity of the stress and the advisable protection. Considerable test data are shown. The test arrangements are described in detail, because new methods had to be devised to obtain the needed data.**

By
J. F. CALVERT
MEMBER A.I.E.E.

F. D. FIELDER
ASSOCIATE A.I.E.E.

Both of the Westinghouse Elec. and Mfg. Co., E. Pittsburgh, Pa.

IT IS the purpose of this paper to consider the magnitudes of the voltages that may be applied to the armature insulation when the armature of an unexcited rotating machine is connected to an energized line. In motors built for the lower and more usual voltages, there is no problem because the amount of turn insulation applied for mechanical strength is enough to withstand the usual voltage requirements. However, on such machines as 13,800-volt line-starting motors, this is not necessarily true, and some further study is required. This problem is one of growing importance because of the desire for full line voltage starting of 11,000 to 13,800 volt motors, and because of the usual desire to bring all rotating a-c machines on the line with a minimum of switching complications.

In the avoidance of dielectric failure, there are 2 insulations to be considered: (1) The armature insulation to ground, which can be damaged only by an appreciable rise in the voltage to ground; and (2) the turn insulation on multiturn armature coils, which can be overstressed only by a large and very sudden change in terminal voltage. If this change in terminal voltage be sufficiently sudden, practically all of it will appear across the turns of the line coil. Obviously, the voltage conditions will be most severe when the machine is connected to the line at the instant when the line potential is a maximum, and the entire armature winding is at zero potential. In any event, the insulation to ground will not be overstressed seriously by connecting the machine to the charged line, because no more than line-to-ground voltage can be applied and voltage reflections can no more than double this. However, if the terminal voltage rise very rapidly to approximately the line-to-ground voltage, a very high potential will exist between the turns of the line coil on a multiturn coil winding. It is this latter condition that will be discussed in this paper. Various external circuit conditions are considered. The test methods are given as well as the data obtained, because considerable difficulty was experienced in devising circuits that would yield the required information, and the testing methods may prove useful in future investigations.

## Observations and Conclusions

1. Switching surges occurring when a machine is thrown directly on the line may overstress the turn insulation of the line end coils on a multiturn coil armature winding. The severity of this stress is greatly affected by the external circuit conditions—that is, whether the machine is connected to an overhead line, to a cable system, or to a transformer. It is affected also by reactors and by parallel capacitances to ground. Test and calculated data are presented to illustrate these cases and to afford methods of making quantitative determinations.

2. The most severe conditions result if the breaker is closed when the line voltage is at its crest value. Test methods were devised by which this condition could be obtained on every application of the switching surge (see figure 8). This permitted the quantitative determination of both the rate of rise of voltage and the "final" value attained before reflections returned to the machine; hence this permitted an actual comparison between test and calculated data.

3. The initial condition in the switching surge is a standing voltage wave with current zero on the incoming lines. In so far as the possibilities of damaging the armature insulation are concerned, this is fundamentally different from the traveling wave phenomena which must be considered in lightning surge studies. In the case of lightning surges, it has been fully demonstrated that for an unprotected machine the maximum overvoltage can overstress the ground insulation, and the maximum rate of rise of voltage can be sufficient to overstress turn insulation. However, it is shown in this paper that the switching surge resulting from connecting a machine to an energized line is not likely to overstress the ground insulation, while the possibility of damage to turn insulation is present for multiturn coil windings of full line voltage, starting on 11,000 to 13,800 volts.

4. When the maximum rate of rise of voltage at the machine terminals is known, the maximum voltage between turns of a multiturn coil winding can be computed (see appendix II). From this it can be determined whether or not the turn insulation should be protected.

5. The maximum rate of rise of voltage and the maximum voltage attained some time during the first few microseconds can be computed with satisfactory accuracy by the methods illustrated in figure 2. For a comparison of calculated and test data, see figures 4, 5, 10, and 11, and reference 7.

6. In the calculations the circuit parameters are assumed to be true constants, yet for commercial circuits this is not actually the case. A study has been made of the differences between test and calculated data introduced by the test variations in the individual circuit parameters in order to show that the various simplifying assumptions are fully justified.

7. Tests show that machine surge impedances are far from constant values as functions of time. However, if they are not so considered the calculations are greatly complicated, for one then has the choice of either representing the machine by a suitable network of lumped constants or expressing the machine surge impedance as a function of time. The latter method of attacking the problem will give rise

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to the use of integral equations of rather complicated form and lead to very involved results. It is especially desirable to maintain simple methods of attack and to obtain simple solutions, so that a great variety of circuits can be considered and usable results found without too great an expenditure of time and effort. Sufficiently accurate solutions are obtained by treating the machine as a constant surge impedance. This machine characteristic is determined by the direct measurement of voltage and current at the line end where the surge is applied to the machine winding (see figure 3).

8. If a lumped inductance be connected in series with the line and the machine winding, then when the breaker is closed it will tend to limit the rate of rise of the machine terminal voltage in the same manner whether this inductance has been connected in series on the line side or on the machine side of the breaker prior to its closing. This fact is stated in rigorous terms together with related data in cases II and III of figure 2.

9. If a capacitance to ground is to be effective in limiting the rate of rise of voltage, it must be connected on the side of the breaker that is not energized before the breaker is closed—that is, on the rotating machine side. This is stated mathematically by cases IV and V of figure 2.

10. If the switching surge result from connecting the rotating machine directly to a transformer, the steepness and magnitude of the rate of rise of terminal voltage on the rotating machine may be very great, because the surge impedance of the transformer can be quite low during the first few microseconds (see figure 7).

11. The protection of turn insulation from switching surges can become a problem only on high-voltage line-starting machines. Any such machine may have to resist exceptionally high voltages between turns. Therefore, it should be sufficiently well insulated between turns to withstand the switching surges to which it may be subjected, regardless of the circuit conditions external to the armature winding. Further than this, the machine insulation should have a reasonable factor of safety. The value of this voltage stress can be estimated by the methods presented in this paper, and the insulation may be designed accordingly. However, it generally is believed that successive over-voltage shocks will weaken the insulation. Also, it is well-known that the dielectric strength will decrease with time, as a result of the slow deterioration of the organic binders used in all armature insulations today. Therefore, for large and important machines that are to be subjected to severe operating conditions, it would be the part of wisdom to have the added safety that can be secured from rationally applied protective apparatus. It is believed that while generalizations should not be made, nevertheless the methods of analysis presented in this paper should point the way to this added protection without showing a serious increase in the over-all installation costs, and usually small capacitors connected to ground from the line terminals of the machine will prove sufficient.

## THEORY AND RESULTS

As a first step in the analysis, a simple electric circuit and a hydraulic analogue are considered, as shown in figure 1. It will be assumed for the present that the breaker ($B$ of figure 1$a$) does not offer an appreciable impedance of any form. Then the closing of the breaker so as to connect the line $Z_1$, which is charged to voltage $E_a$, to the uncharged line $Z_2$ is analogous to the opening of the gate ($G$ of figure 1$b$) so as to connect the channel reservoir $Z_1$ containing an incompressible fluid of low viscosity at the height $E_a$ to the channel $Z_2$. In each case the reservoir of potential energy in $Z_1$ raised to the height $E_a$ is partially converted into the kinetic energy of flow in $Z_2$ by a drop in potential or head from $E_a$ to $E_2$. The front of $E_2$ and that between $E_a$ and $E_1$ proceed away from the junction of $Z_1$ and $Z_2$ with equal speeds in opposite directions, and in actual practice these fronts are attenuated or sloped off by frictional or energy dissipating effects.

The foregoing explanation gives a fairly reasonable representation of the phenomena existing during the first few microseconds of a switching surge. It is shown as case I of figure 2. The derivations of the mathematical expressions given as cases I and IV of figure 2 have been presented by one of the authors of this paper in a discussion of a previous paper.[7] Figure 2 of the present paper shows several other circuits for which the performance has been computed. As the methods of derivation are all similar to those shown in the discussion just mentioned, none will be illustrated here.

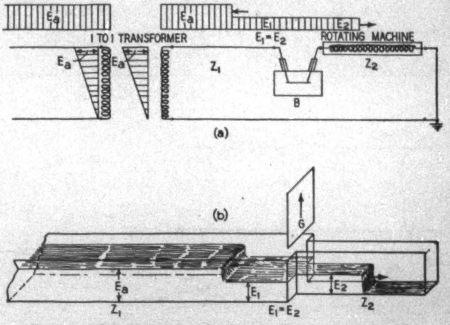

**Fig. 1.** Voltage distribution a few microseconds after breaker B is closed (a) and a hydraulic analogy (b)

In reference 7, test data were presented to illustrate case IV of figure 2, except that for the test the machine surge impedance $Z_2$ was replaced by a noninductive resistance $R$ and no breaker was used, only sphere gaps. The test and calculated data were in very close agreement both as to final value and rate of rise. Two values of $C$ were used, one of which was 6 times the other. This agreement proved the reliability of the methods of calculation when the circuit parameters are truly lumped constants.

The next question is: How closely will these simple circuit constants represent the conditions in actual practice, and how closely will the relatively simple methods of calculation shown in figure 2 agree with tests made to simulate operating conditions? Obviously, the treatment of a line as a surge impedance, and of a commercial capacitor as a true capacitance, is above reproach for such short periods of time as are to be considered here. Consideration now will be given to the effect of the circuit breaker, the treatment of the rotating machine winding as a constant surge impedance, and the treatment of a commercial 60-cycle air-core reactor as a lumped inductance. Unless the effects of these assumptions are understood fully, the relatively simple solutions given in figure 2 could not be depended upon for making reasonably accurate calculations. The approximations will be discussed in the preceding order.

In the tests to be discussed next, a standard 13.8 kv breaker was used in the circuit. It had a meas-

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[7] For all references see list at end of paper.

Fig. 2. Voltage and current transients for different circuits, following the closing of the breaker

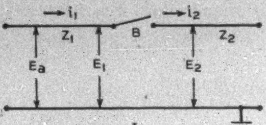
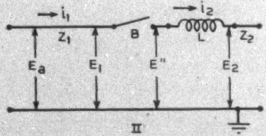
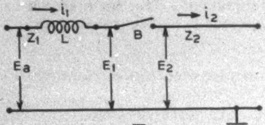
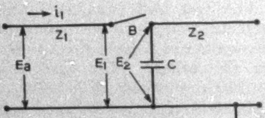
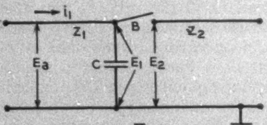
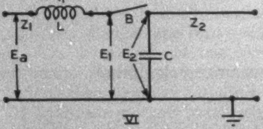
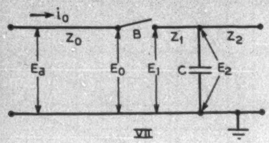
| Circuit | Initial Condition Before Breaker B Is Closed | Transient Values at Time t After Breaker B Is Closed |
|---|---|---|
|  <br>I | $E_1 = E_a$<br>$i_1 = i_2 = 0$<br>$E_2 = 0$ | $E_2 = \frac{E_aZ_2}{Z_1 + Z_2}$<br>$i_1 = i_2 = \frac{E_a}{Z_1 + Z_2}$<br>$\frac{dE_2}{dt}\Big/ o < t < \Delta t = \infty$ |
|  <br>II | $E_1 = E_a$<br>$i_1 = i_2 = 0$<br>$E'' = E_2 = 0$ | $E'' = E_a\left[\frac{Z_2}{Z_1 + Z_2} + \frac{Z_1}{Z_1 + Z_2}\epsilon^{-\frac{(Z_1 + Z_2)t}{L}}\right]$<br>$E_2 = \frac{E_aZ_2}{Z_1 + Z_2}\left[1 - \epsilon^{-\frac{(Z_1 + Z_2)t}{L}}\right]$<br>$i_1 = i_2 = \frac{E_a}{Z_1 + Z_2}\left[1 - \epsilon^{-\frac{(Z_1 + Z_2)t}{L}}\right]$<br>Maximum rate of rise of voltage $E_2$ is<br>$\frac{dE_2}{dt}\Big/_{t=0} = \frac{Z_2}{L}E_a$ |
|  <br>III | $E_1 = E_a$<br>$i_1 = i_2 = 0$<br>$E_2 = 0$ | $E_2 = \frac{E_aZ_2}{Z_1 + Z_2}\left[1 - \epsilon^{-\frac{(Z_1 + Z_2)t}{L}}\right]$<br>$i_1 = i_2 = \frac{E_a}{Z_1 + Z_2}\left[1 - \epsilon^{-\frac{(Z_1 + Z_2)t}{L}}\right]$<br>Maximum rate of rise of voltage $E_2$ is<br>$\frac{dE_2}{dt}\Big/_{t=0} = \frac{Z_2}{L}E_a$ |
|  <br>IV | $E_1 = E_a$<br>$i_1 = 0$<br>$E_2 = 0$ | $E_2 = \frac{E_aZ_2}{Z_1 + Z_2}\left[1 - \epsilon^{-\frac{(Z_1 + Z_2)t}{Z_1Z_2C}}\right]$<br>$i_1 = \frac{E_a}{Z_1 + Z_2}\left[1 + \frac{Z_2}{Z_1}\epsilon^{-\frac{(Z_1 + Z_2)t}{Z_1Z_2C}}\right]$<br>Maximum rate of rise of voltage $E_2$ is<br>$\frac{dE_2}{dt}\Big/_{t=0} = \frac{E_a}{Z_1C}$ |
|  <br>V | $E_1 = E_a$<br>$i_1 = 0$<br>$E_2 = 0$ | $E_2\Big\vert_{t>\delta>0} = E_a\left[\frac{Z_2}{Z_1 + Z_2}\left(1 - \epsilon^{-\frac{(Z_1 + Z_2)t}{Z_1Z_2C}}\right) + \epsilon^{-\frac{(Z_1 + Z_2)t}{Z_1Z_2C}}\right]$<br>$i_1 = \frac{E_a}{Z_1 + Z_2}\left[1 - \epsilon^{-\frac{(Z_1 + Z_2)t}{Z_1Z_2C}}\right]$<br>$\frac{dE_2}{dt}\Big/_{t=0} = \infty$ |
|  <br>VI | $E_1 = E_a$<br>$i_1 = 0$<br>$E_2 = 0$ | Where $\alpha^2 > \omega^2$, use<br>$E_2 = \frac{E_aZ_2}{Z_1 + Z_2}\left[1 - \epsilon^{-\alpha t}\left(\cosh\sqrt{\alpha^2 - \omega^2}\,t + \frac{\alpha\sinh\sqrt{\alpha^2 - \omega^2}\,t}{\sqrt{\alpha^2 - \omega^2}}\right)\right]$<br>Where $\alpha^2 < \omega^2$, use<br>$E_2 = \frac{E_aZ_2}{Z_1 + Z_2}\left[1 - \epsilon^{-\alpha t}\left(\cos\sqrt{\omega^2 - \omega^2}\,t + \frac{\alpha\sin\sqrt{\omega^2 - \alpha^2}\,t}{\sqrt{\omega^2 - \alpha^2}}\right)\right]$<br>Where $\alpha^2 = \omega^2$, use<br>$E_2 = \frac{E_aZ_2}{Z_1 + Z_2}\left[1 - \epsilon^{-\alpha t}(1 + \alpha t)\right]$ $\quad i_1 = \frac{E_2}{Z_2} + C\frac{dE_2}{dt}$ |

**Fig. 2 continued. Voltage and current transients for different circuits, following the closing of the breaker**



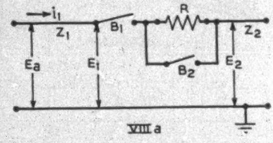
$$E_0 = E_a$$
$$i_0 = 0$$
$$E_1 = E_2 = 0$$

$$E_2 = \frac{E_aZ_1}{(Z_0 + Z_1)}\left[\frac{2Z_2}{Z_1 + Z_2}\right]\left[1 - \epsilon^{-\frac{(Z_1 + Z_2)t}{Z_1Z_2C}}\right]$$

Until reflected, waves return from the junction of $Z_0$ and $Z_1$

Maximum rate of rise of voltage $E_2$ is

$$\frac{dE_2}{dt}\Big/_{t=0} = \frac{2E_0}{C(Z_0 + Z_1)}$$



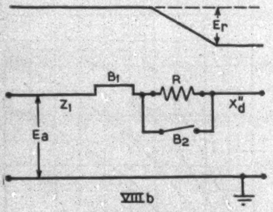
Initial condition before breakers $B_1$ or $B_2$ is closed

$$E_1 = E_a$$
$$i_1 = 0$$
$$E_2 = 0$$

Condition after closing breaker $B_1$ and leaving $B_2$ open

$$E_1 = E_a\frac{(Z_2 + R)}{Z_1 + Z_2 + R}$$

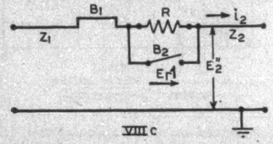
$$E_2 = \frac{E_aZ_2}{Z_1 + Z_2 + R}$$



Surge condition replaced by 60 cycle a-c transient

Intermediate condition

$$E_r/\max = \frac{RE_a}{\sqrt{(X_d'')^2 + R^2}}$$



Initial condition (voltage across $B_2$ is $E_r$)

After $B_2$ closes, the transient due to the voltage $E_r$1 alone is

$$E_2'' = \frac{(R + Z_1)Z_2E_r}{R(Z_1 + Z_2) + 2Z_1Z_2}$$

ured capacitance to ground of 0.00032 microfarad, which was included in all calculations, and which in some instances had a noticeable effect.

The effects of assuming the machine surge impedance $Z_2$ to be a constant will be considered now. The surge impedance of the rotating machine armature winding was measured by applying a surge voltage to a noninductive resistor connected in series with the machine (see figure 3). Thus, from a determination of the voltage applied to the machine and the current flowing, the impedance was determined. It was anything but constant, with values ranging from about 200 or 300 ohms up to 1,000 ohms; and yet if easily applied formulas are to be used, this impedance must be regarded as a constant. It may be observed in figure 3 that the surge impedance is fairly constant between 1 and 5 microseconds with an average value of about 950 ohms, and this is the range of primary importance. Using this value and referring to case IV of figure 2, the test and calculated data are as shown in figure 4. These agree well until an appreciable part of the voltage rise occurs within the first microsecond, where the machine surge impedance is much less than the assumed value of 950 ohms. In this range, the machine will take more current than calculated, and thus will retard the rate of rise of voltage somewhat more than would a constant machine surge impedance of 950 ohms.

Figure 5 shows data for case VI of figure 2. As in the examples discussed in the last paragraph, the calculated data, in general, errs on the safe side and apparently for the same reason. It is reasonable to suppose at first that, because the air core reactor no longer will act as a pure inductance, this would be a contributing factor to the discrepancy between calculation and test. Figure 6 shows the measured impedance of the reactor and a calculated impedance on the assumption that the reactor acts as an inductance and capacitance in parallel. (The calculated curve has been made a little high for reasons that will be made clear in appendix I.) It is apparent that during the first fraction of a microsecond or so the effective parallel capacitance will by-pass current through the equivalent reactor, thus tending to give an even more rapid rise to the voltage than if it were neglected. The effects of the 2 simple assumptions made in accordance with case VI of figure 2 are to be considered, namely: (1) that the machine surge impedance is taken as a constant value of 950 ohms, and (2) that only the 60 cycle value of the inductance is used to represent the reactor. When these are compared with actual conditions, the actual capacitance between the turns of the reactor tends to make the initial rate of rise of voltage more rapid than calculated, while the actual initial low surge impedance of the rotating machine tends to make the initial rate of rise less rapid than do the assumptions upon which the calculations are based. However, it is believed that the distributed capacitance to ground of the reactor is an even more important factor. Neglecting this in the calculations gives a rate of rise more rapid than it should be. Further calculations to illustrate these facts are given in appendix I.

The last test case to be discussed is that shown in figure 7*a*. Here the machine is connected directly to a transformer. It may be seen that the rate of rise of voltage is tremendously great, and that it is marked by severe oscillations. However, in addition to the transformer, there was quite a network of apparatus between the machine and the generator supplying the voltage. The surge impedance measured for the supply circuit from the breaker end proved to be decidedly variable with time. The supply generator contributed little to the effect, because practically the same curves as those shown in figure 7*b* were obtained when the generator shown on the wiring diagram for that figure was short-circuited.

Approximate calculations can be made for the conditions shown in figure 7*a* by assuming a suitable constant value for the transformer surge impedance. The maximum rate of rise can be approximated with this assumption, but the oscillations cannot. In general, it can be concluded that such a connection is not necessarily a very safe one; the possibilities for severe stresses on the turn insulation during a switching surge seem quite as likely here as with other types of external circuits.

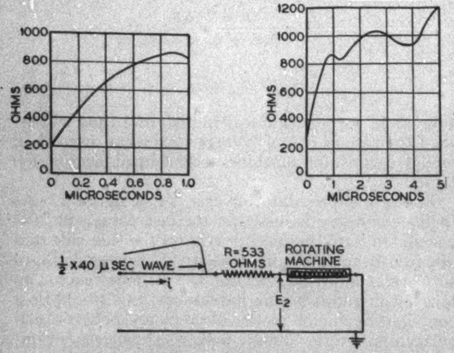


**Fig. 3. Surge impedance of a rotating machine**

Perhaps the only other feature in figure 2 that requires further explanation is case VIII. This is intended to show a machine being connected to an incoming line or cable in 2 steps. Case VIII*a* shows the machine or surge impedance $Z_2$ being connected to the line $Z_1$ with a resistance $R$ in series, by the closing of $B_1$. This limits the voltage $E_2$, as shown. However, before this resistance can be cut out, the voltage distribution becomes that shown in case VIII*b*, where $X_d''$ is the subtransient reactance of the rotating machine. If it happen then that $B_2$ closes as quickly as possible after $B$, but when $E_r$ is at crest value, then the voltage and current conditions will be as shown in case VIII*c*. The following numerical example will illustrate that for these very high speed switching transients, the duration of which is of the order of only a few microseconds, a considerable part of the beneficial reduction in severity of the rise of voltage at the machine terminals is lost even when the most suitable value of $R$ is chosen.

Assume

$Z_1 = 10$ ohms
$X_d'' = 20$ ohms
$Z_2 = 190$ ohms
$R = 50$ ohms

Then when the resistance is first cut in (case

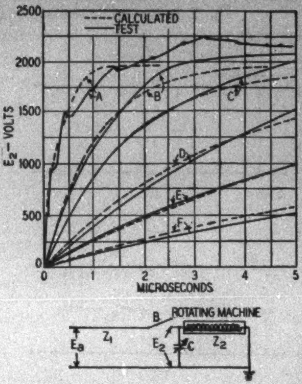


**Fig. 4. Tests and calculated values of $E_2$ for case IV of figure 2**

$Z_1$ = 550 ohms
$Z_2$ = 950 ohms
$E_a$ = 3,110 volts
Values of C were:

| Curves | Microfarads |
|---|---|
| *A* | 0.00072 |
| *B* | 0.00272 |
| *C* | 0.00472 |
| *D* | 0.01072 |
| *E* | 0.02072 |
| *F* | 0.04072 |

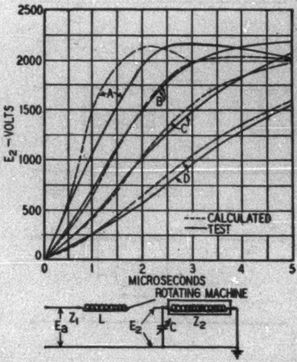


**Fig. 5. Test and calculated values of $E_2$ for case VI of figure 2**

$Z_1$ = 550 ohms
$Z_2$ = 950 ohms
$L$ = 0.486 millihenry
$E_a$ = 3,110 volts
Values of C were:

| Curves | Microfarads |
|---|---|
| *A* | 0.00072 |
| *B* | 0.00272 |
| *C* | 0.00472 |
| *D* | 0.00872 |

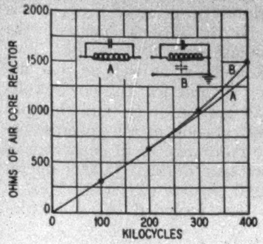


**Fig. 6. Measured impedance of the reactor used in the circuit of figure 5. Curves A and B show values for the corresponding circuits**

o—Points calculated from values used for curve *B* of figure 12

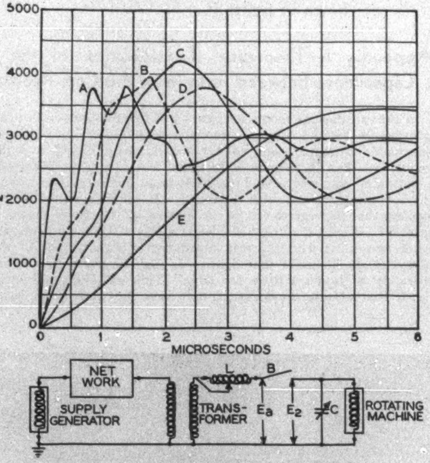


**Fig. 7a. Test values of $E_2$ with the machine connected directly to a transformer as shown in the diagram**

| Curve | C in Microfarads | L in Millihenries |
|---|---|---|
| *A* | 0.00072 | 0 |
| *B* | 0.00272 | 0 |
| *C* | 0.00472 | 0 |
| *D* | 0.00872 | 0 |
| *E* | 0.00072 | 1.16 |

VIII*a*), $E_2 = 0.76\ E_a$. During the transition stage (case VIII*b*), $E_r = 0.93\ E_a$; and when the resistance is cut out (case VIII*c*), $E_2'' = 0.77\ E_a$ due to the transient only. Thus, instead of a sudden rise of 50 per cent in voltage on each step, it can be more than 75 per cent even with the best choice of $R$ for the particular machine and line constants assumed.

It should be observed that the circuit constants used in the test arrangements for figures 4 and 5 in some respects do not show conditions that are nearly as severe for the rotating machine as they might be. In these tests it was necessary to use an overhead line with a surge impedance of 550 ohms, simply because a sufficiently long cable was not so easily obtained. In actual practice, the impedance might be far less with an incoming cable circuit, and the conditions would be made correspondingly more severe for the machine. Thus, if $Z_1$ were lower, then not only would the "final" value be higher, but larger values of $C$ or $L$ would be required to reduce the rate of rise of voltage.

## TEST METHODS

In making the laboratory tests, the problem was to close a 60 cycle circuit at the crest of the wave applying power from a source to the windings of a machine, and to record the first few microseconds of the resulting transient. Much thought and experimentation were required in obtaining circuits that would produce results without introducing extraneous effects and that would yield duplicate data on repeated tests. The circuit that operated most successfully, and the test procedure, are described in detail in the following paragraphs.

An established method of recording transient voltages of circuit breaker operations has been the employment of a cathode ray oscillograph equipped with a rotating film drum. This method was not suitable for these tests, however, because the highest practical film speed with a rotating drum represents a time scale in the order of 400 microseconds per inch. The rate of rise of voltage on these switching surge tests was such that a time scale of the order of 1 microsecond per inch was required for accurate measurements.

When such short-time records are required, it is necessary to initiate the timing system of the cathode ray oscillograph slightly in advance of the application of the voltage wave in order to obtain the complete wave. A standard method of securing this delay is to pass the voltage wave through a suitable length of cable. For example, a wave traveling through a 250 foot cable will be delayed about $^1/_2$ microsecond in transmission. However, the direct use of a delay cable was not permissible in these switching tests, because the 50 to 60 ohm surge impedance of a cable directly connected to the terminals of the machine under test would introduce a major change in the external circuit constants and thus would modify any data obtained.

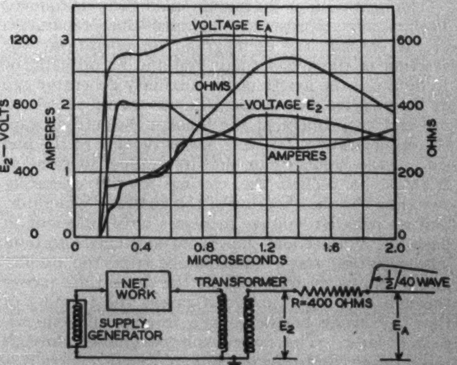


**Fig. 7b. Surge impedance of transformer and supply circuit from breaker end**

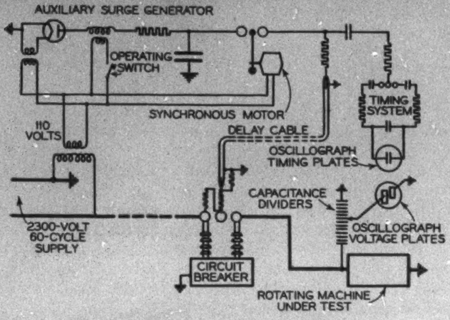

AUXILIARY SURGE GENERATOR
OPERATING SWITCH
SYNCHRONOUS MOTOR
110 VOLTS
DELAY CABLE
TIMING SYSTEM
OSCILLOGRAPH TIMING PLATES
CAPACITANCE DIVIDERS
2300-VOLT 60-CYCLE SUPPLY
OSCILLOGRAPH VOLTAGE PLATES
CIRCUIT BREAKER
ROTATING MACHINE UNDER TEST

**Fig. 8. Diagram of connections for test**

Several circuit connections and auxiliary devices were tried before good results were obtained. In the first attempts the synchronizing of the timing system of the oscillograph with the application of the 60 cycle crest voltage either failed entirely or was too erratic in its behavior to be relied upon. In other trials the tripping circuits introduced oscillations of such magnitudes that correct interpretation was impossible.

The circuit finally employed is shown in figure 8. The features of this circuit include: (1) time delay for oscillograph operation by means of a cable in the tripping system instead of the measuring system; (2) high resistance connection from the tripping surge to prevent extraneous effects from being superimposed upon the power voltage; (3) synchronizing on the crest of the 60 cycle wave with a synchronous motor gap; (4) circuit breaker closing replaced with sphere gaps on the breaker terminals to obtain the effect of closing the breaker without the unpredictable time variation in actually operating the breaker contacts; (5) capacitance dividers for measuring voltages without introducing undesirable impedances in the external circuit constants of the machine.

The operation of the circuit was briefly as follows: Preliminary adjustments included the preparation of the cathode ray oscillograph for operation; the starting of the synchronous gap and its adjustment to diminish the length of the auxiliary generator gap at the positive crest of the 60 cycle wave; the cleaning and adjustment of the breaker 3-electrode gap; the application of 60 cycle power voltage to the line side of the breaker gap, and its gradual increase to 2,200 volts. Then the closing of the operating switch starts the charging of the auxiliary generator, and its negative voltage increases until sufficient to flash the synchronous gap in its shortened position. The resulting surge immediately trips the oscillograph timing system, and at the same time passes through the delay cable and causes the tripping of the 3-electrode breaker gap a fraction of a microsecond later. The power voltage follows through the breaker gap to the machine terminals, where it is measured by the cathode ray oscillograph through the capacitance divider system.

With details of the circuit properly arranged, it was relatively simple to make the various changes in the external circuit and secure data for the tests illustrated in figures 4, 5, and 7*a*, as well as that described in reference 7. In practice, the power voltage burned the breaker gap severely, and this gap had to be replaced (by rotation of the spheres) between each test. The relatively small capacitances to ground of the capacitance divider (0.0004 microfarad) and the uncharged parts of the circuit breaker (0.00032 microfarad) were included in all calculations.

Oscillograms typical of those obtained in these tests are shown in figure 9.

## Appendix I—Theoretical Consideration of the Capacitance Between Turns in an Air Core Reactor

In the calculations shown for case VI of figure 2 and used in calculating the curves for figure 5, the most simple assumption possible was made for the reactance, namely, that it varied directly with the frequency—that is, a pure inductance was assumed. However, it was an air core reactor and obviously had some capacitance coupling between turns and some to ground. It will be assumed for the moment that the reactor can be represented by the circuit shown in figure 6*A*. Placing $L = 0.486$ millihenry and $c_1 = 0.00006$ microfarad, a fair agreement with the test impedance is obtained out to 400 kilocycles, as shown in that figure. It may be noted that $c_1$ deliberately is chosen a little too large. This will bring out more clearly that its influence does not prove to be the cause of the varia-

Corresponds to left-hand part of figure 6 of reference 7; line, resistance, and capacitance divider

Corresponds to right-hand part of figure 6 of reference 7; line, resistance, and capacitance divider

Corresponds to figure 4 of this paper, curves *A*

Corresponds to figure 5 of this paper, curves C

Corresponds to figure 7b

A—Applied wave
B—Voltage across series resistance
C—Voltage at machine terminals

**Fig. 9. Typical oscillograms obtained in the tests described in this paper**

tion between test and the more simply calculated data of figure 5.

The circuit shown in figure 11 will be considered for the time immediately after the breaker is closed. Let

$$\left.\begin{aligned} E' &= \left(Z_1 + \frac{Lp}{1 + Lc_1p^2}\right)i \\ E'' &= iZ_2 \\ E' + E'' &= E_a\mathbf{1} \end{aligned}\right\} \tag{1}$$

Then

$$E'' = E_2 = \frac{E_aZ_2}{Z_1 + Z_2}\,\frac{p^2 + \omega^2}{p^2 + 2\alpha p + \omega^2}\,\mathbf{1} \tag{2}$$

where

$$\alpha = \frac{1}{2c_1(Z_1 + Z_2)}$$

$$\omega^2 = \frac{1}{Lc_1}$$

and where $L$ and $c_1$ are the values shown in figure 6. From the foregoing:

If $\alpha^2 > \omega^2$,

$$E_2 = \frac{E_aZ_2}{Z_1 + Z_2}\left[1 - \frac{2\alpha\epsilon^{-\alpha t}}{\sqrt{\alpha^2 - \omega^2}}\sinh\sqrt{\alpha^2 - \omega^2}t\right] \tag{3a}$$

If $\alpha^2 < \omega^2$,

$$E_2 = \frac{E_aZ_2}{Z_1 + Z_2}\left[1 - \frac{2\alpha\epsilon^{-\alpha t}}{\sqrt{\omega^2 - \alpha^2}}\sin\sqrt{\omega^2 - \alpha^2}t\right] \tag{3b}$$

If $\alpha^2 = \omega^2$,

$$E_2 = \frac{E_aZ_2}{Z_1 + Z_2}\left[1 - 2\alpha t\epsilon^{-\alpha t}\right] \tag{3c}$$

It is intended to show the effect of considering the capacitance between turns in the reactor by comparing the preceding calculation with that obtained by the use of case II or III of figure 2, and with test. The test data cannot be obtained directly because some capacitance to ground is necessary at the machine terminal when measurements are made. For theoretical purposes, there is enough test data in figure 5 to permit the desired data to be obtained by extrapolation. This is done in figure 10. The desired points are those at $C = 0$ in the latter figure. These are replotted in the test curve of figure 11. Equation $3a$ is used for curve $B$ of figure 11, and case II or III of figure 2 is used to obtain curve $A$ of figure 11.

From these results one may conclude that the neglecting of the capicitance between the turns of the reactor was not an important matter. The difference between test and calculation in figure 11 is ascribable in part to the variation in the surge impedance of the rotating machine, which in the calculations has been assumed to have a constant value of 950 ohms, as was done in the previous calculations; but by this process of elimination the difference in test and calculated data shown in that figure must be attributable primarily to the distributed capacitance to ground of the commercial reactor which has been neglected in the calculated data.

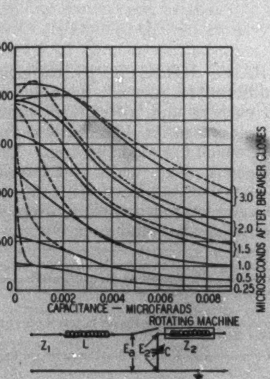
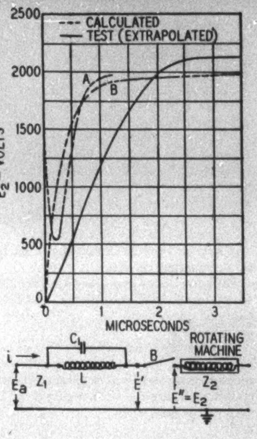


**Fig. 10. Composite curves from figure 5 used to obtain curves in figure 11**

$Z_1$ = 550 ohms
$Z_2$ = 950 ohms
$L$ = 0.486 millihenry
C—variable

**Fig. 11. Test and calculated values of $E_2$ for circuit shown, to illustrate the effect of considering the capacitance between turns in the reactor**

$C_1$ = 0 for curve $A$
= 0.00006 microfarad for curve $B$
$Z_1$ = 550 ohms
$Z_2$ = 950 ohms
$L$ = 0.486 millihenry
$E_a$ = 3,110 volts



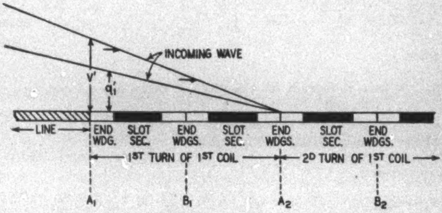


**Fig. 12. A simplified diagram in which the machine winding is considered as a line, and electromagnetic and electrostatic coupling between turns is neglected**

$V_1'$ = voltage; $q_1'$ = charge per unit length

## Appendix II—Voltage Between Turns in the Line End Armature Coils

It was stated earlier in the paper that once the maximum rate of rise of voltage at the machine terminals was known, the maximum voltage between turns could be estimated. It is intended now to review briefly how this may be done.

First, if the winding be considered merely as a line and electromagnetic and electrostatic coupling between turns be neglected, a simplified picture of the phenomena is obtained, as is illustrated in figure 12. When the incoming voltage wave has just gone around one turn to reach the point $A_2$, which physically is directly under $A_1$, the voltage $V_1$ would be that existing between $A_1$ and $A_2$. Actually, however, other voltages and currents are induced in the other turns of this line-end coil. To show this more clearly, the turns may be redrawn as shown in figure 13, where $V$ represents the voltage and $q$ the net charge per unit length. The subscripts indicate the number of the "lines" shown in the figure, and the single primes are used for waves traveling to the right, while the double primes are used for waves traveling to the left. From figure 13, it may be seen that the maximum voltage between turns exists between points $A_1$ and $A_2$, and that it is attained at the instant when the waves have just come back under themselves. This maximum voltage difference will be designated as $(V_1' - V_2')$ max.

Up to this instant the problem may well be considered as $n$ transmission lines, with the one discontinuous where the surge enters at $A_1$. (The discontinuity in the outgoing line at $A_4$ is neglected, because the charge on the section $B_3$ to $A_4$ is proportionately quite small.) It must be pointed out here that this is not at all the same problem as having all the lines continuous in both directions, because if this were the case $q_1$ would have traveled both right and left, and the effects on the other lines would have been to leave no net charges on them.

However, it is possible to relate these 2 solutions: (1) the case where line 1 is discontinuous, and (2) the case where line 1 is continuous; and from this relationship simple solutions for case 1 are obtained.[5]

Assume that the speed of the wave along the coil in the slotted section is 10,000 miles per second, and in the end winding 125,000 miles per second,[2,5] and assume that the rate of rise of voltage is constant during the time required for the wave to travel around one turn of the coil; then

$$t_t = \frac{1}{63.36}\left[\frac{2l_c}{10} + \frac{MT - 2l_c}{125}\right] \times 10^{-6} \qquad (4)$$

where

$t_t$ = time in seconds for the wave to travel around one turn of the coil
$l_c$ = length of core in inches
$MT$ = armature mean turn in inches.

Now assume

$$V_1' = Gt_t, \qquad (5)$$

where $G$ is the maximum rate of rise of voltage at the machine terminals in volts per second.

Then the maximum voltage between turns 1 and 2 (at $A_1$ and $A_2$) is

$$(V_1' - V_2') \text{ max.} = \xi b(G)t_t \qquad (6)$$

where $\xi b$ is a constant depending on the capacitance coupling from turn to turn and from turn to ground, and also depending on the number of turns per coil, $n$. As already indicated, the derivation of $\xi b$ is given in an earlier paper.

The value $\xi b$ is shown in curve form in figure 11 of reference 5. Figure 15 of that reference shows close agreement between test and calculated data obtained by the use of the methods outlined here.

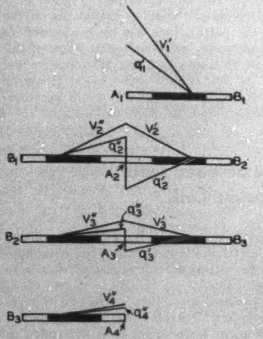


Fig. 13. Representation of a multiturn winding where the electrostatic and electromagnetic couplings between turns are considered

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# Electric Shock Effects of Frequency

Supplementing earlier research progress reports[1] concerning the physiological effects of electric shock, the authors here present the results of a series of experiments made to determine the heart reaction to currents of different frequencies.

By
**W. B. KOUWENHOVEN**
FELLOW A.I.E.E.

**D. R. HOOKER***
NONMEMBER A.I.E.E.

**E. L. LOTZ**
ENROLLED STUDENT

All of The Johns Hopkins Univ., Baltimore, Md.

HEART REACTIONS to electric shock currents of different frequencies, including both interrupted direct current and alternating current, have been the subject of a series of laboratory experiments the results of which are reported here. In the conduct of the research, dogs, under full morphia-ether anesthesia, served as subjects, with the chest open in each case and electrodes applied directly to the heart. In each test, the minimum current for

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* Member of the American Physiological Society and of the American Medical Association.

[1] For all numbered references, see list at end of article.

the given frequency and type of current required to produce ventricular fibrillation was measured.

Conclusions drawn from the results of this investigation include the following:

1. That with interrupted direct current the dog heart is most readily thrown into fibrillation by currents the frequency of interruption of which lies in the neighborhood of 60 per second.

2. That with interrupted direct current the musculature of the heart becomes more responsive as the frequency is increased from zero, responding most readily to shocks lying between 40 and 100 interruptions per second. As the frequency of interruption is increased beyond this range the heart is less responsive and requires greater values of current to establish ventricular fibrillation.

3. That with alternating current there is little if any significant difference in the reaction of the heart to shocks from 25 and 60 cycle circuits.

## CURRENT SUPPLY

In the tests with interrupted direct current the source of supply was a 110 volt direct current circuit. The current from this source was interrupted at regular intervals by means of a motor driven commutator type of interruptor. The brushes making contact with the commutator were carefully adjusted so as to close the circuit for one half of each cycle and open it for the other half. The number of shocks per second, or the frequency, was varied from 2 to 1,200 by adjusting the speed of the driving motor. The oscillogram of figure 1 shows the wave shape of the interrupted direct current at a frequency of 60 cycles per second. A low-range direct-current milliammeter, indicating the mean value of the current, was used to measure the current passing through the heart. The maximum value is obtained by multiplying the reading by the factor 2.

In the tests where alternating current was used, the source of supply was a small rotary converter the speed of which was varied to obtain frequencies ranging from 25 to 60 cycles per second. Current applied to the animal was taken from the secondary of a transformer energized by the convertor. The effective value of the alternating current passing through the heart was measured by means of a copper oxide rectifier and a sensitive direct current instrument. The maximum value is given by multiplying the instrument reading by 1.41.

Series resistors in the circuit were used to regulate the value of the current supplied to the heart. A special switch, driven by a synchronous motor, was inserted in the line to control the duration of the shock. In all tests the duration of the current flow was maintained at 2 seconds.

## PROCEDURE

As already stated the animals were placed under full anesthesia, and the chest opened, with artificial respiration maintained. The heart was protected from cooling by the heat from an incandescent bulb provided with a suitable reflector. A small slit was made in the pericardium at the apex of the heart for the insertion of the electrodes. These consisted of 2 small needles, 3 millimeters long and spaced 2 millimeters apart, which were inserted in the heart musculature at the apex.[1] These needles were provided with insulating shoulders that prevented their insertion in the heart to a depth of more than 2 millimeters. They were mounted in a hard rubber holder and backed by springs so that full contact could be maintained with the heart. The holder was held in the hand during the application of the shock.

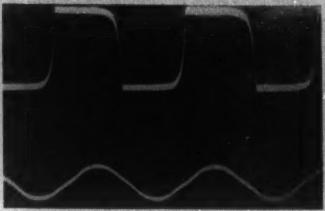

**Fig. 1. Wave shape of interrupted direct current**

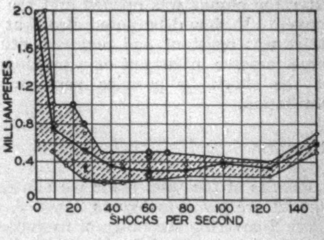

**Fig. 2. Mean values of interrupted direct current required to cause fibrillation**

While the animal was being made ready, the frequency was adjusted to the desired value and the series resistance set to supply a small value of current. When all was ready the electrodes were inserted and the circuit closed for a period of exactly 2 seconds, after which the needle electrodes were removed. The effect upon the heart was noted and the current measured. If the shock did not produce ventricular fibrillation, the number of interruptions per second or the frequency was changed to a new value and the test repeated after a suitable interval. If the value of current chosen did not cause permanent fibrillation at any of the frequencies tried, it was increased by 0.1 milliampere and the procedure repeated.

When a current value was reached which at a given frequency threw the ventricles of the heart into a permanent fibrillation that persisted after the needle electrodes were removed, a countershock[2] was applied to recover the heart. This brought the heart to rest and beats followed. Following the recovery of the heart after the countershock, it was allowed to rest for a period of from 10 to 15 minutes or more, or until it resumed normal operation.

Then, to determine the relative irritability of the heart, tests were made at other frequencies, using the same value of current which had produced permanent fibrillation at the given frequency. In many of the tests the heart would fibrillate during the 2 second period while the circuit was closed, but would spontaneously resume normal beating when the time switch opened. In such cases the current

**Table I—Values of Fibrillating Current in Milliamperes**

| Frequency Cycles per Second | Interrupted Direct Current Mean | Interrupted Direct Current Maximum | Alternating Current Effective | Alternating Current Maximum |
|---|---|---|---|---|
| 25 | 0.52 | 1.04 | 0.81 | 1.14 |
| 40 | 0.35 | 1.70 | 0.71 | 1.00 |
| 60 | 0.31 | 0.62 | 0.75 | 1.06 |

values are not reported. In the results discussed in the following paragraphs the current values are only for those cases where the fibrillation persisted after the circuit was opened and the electrodes removed. It should be noted also that an occasional heart was resistant and required either an unduly large increase in current or a prolonged application of the shock to produce permanent ventricular fibrillation.

## RESULTS

Results of the tests made with interrupted direct current are given in figures 2 and 3, the curves of figure 2 covering the range of frequencies up to 150 shocks per second, while the curve of figure 3 shows the average fibrillating current for frequencies from 10 to 1,200 cycles per second.

In figure 2 the small circles indicate ammeter readings of the currents that produced permanent ventricular fibrillation at each frequency. Concentric circles indicate that the same current value was noted in 2 or more separate tests. The upper and lower curves of figure 2 respectively show the maximum and minimum fibrillating currents measured, and the crosshatched area between them represents the range of currents found for the different animals studied. The heavy curve drawn through the crosshatched area is the curve of the average current required to produce permanent ventricular fibrillation.

In figure 3 the average or mean current curve of figure 2 is reproduced and the curve is extended to cover the data for the entire range of frequencies of interrupted direct current that was studied.

A study of the results given in figure 2 shows that below 10 shocks per second considerable current was required to produce permanent fibrillation. At a frequency of 2 shocks per second currents of 3 or 4 milliamperes failed to cause fibrillation; instead merely accentuating muscular contractions of the heart that followed the rhythm of the stimulus. As the frequency was increased the heart had greater and greater difficulty in keeping pace with the electrical stimulus until, in the range of 8 to 10 cycles per second, it faltered and relatively low values of current were sufficient to destroy its rhythm. Individual animals differed considerably as shown by the spread of the results, but the curves show clearly that the heart was most sensitive to currents the frequency of interruption of which lay within the range from 40 to 100 cycles per second. In this range very small values of current were sufficient to produce fibrillation. At a frequency of 60 shocks per second the average mean current was found to be 0.31 milliampere.

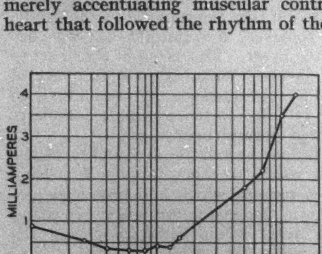

**Fig. 3.** Average value of interrupted direct current required to cause fibrillation

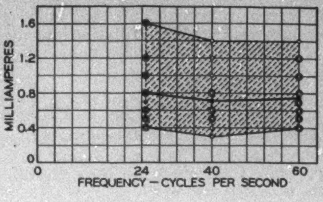

**Fig. 4.** Effective values of alternating current required to cause fibrillation

From the curves of both figures 2 and 3 it is evident that, as the frequency of interruptions was increased above 100 per second, more current was required to establish fibrillation. At 1,260 shocks per second the average current found for the animals tested was 4 milliamperes, or more than 12 times the value at 60 cycles.

Results obtained with alternating current at 25, 40, and 60 cycles are given in figure 4 where the range fibrillating current at these frequencies is shown by the cross hatched area. As is clearly indicated by the spread in the readings, the reaction of individual animals to the current differed to an extent even greater than was found for the interrupted direct current. Also it is evident that a greater value of alternating current than of interrupted direct current is required to produce fibrillation. This is most clearly brought out by comparison of the average and maximum values of fibrillating current at the same frequencies. These values are given in table I.

A study of the alternating current results (figure 4) shows that the hearts of 25 per cent of the animals tested were more easily thrown into ventricular fibrillation by 25 cycle currents than by those of 60 cycles, and that 33 per cent were more sensitive to 60 cycle than to 25 cycle shocks. In the remaining 42 per cent of the tests the effects of the 2 frequencies were identical.

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# Induction Motors Under Unbalanced Conditions

By
**EDWARD O. LUNN**[*]
ASSOCIATE A.I.E.E.

University of British
Columbia, Vancouver

**A general equation (17) for the output of an induction motor operating under unbalanced conditions of applied voltage and primary and secondary impedance, is deduced in terms of frequency of applied voltage, slip, and rotor copper losses. General equations for the currents flowing in the windings are given in appendix I, from which the secondary copper losses, and hence the output and torque, may be calculated. Special conditions of partial unbalance also are considered.**

GENERAL characteristics of induction motors operating under balanced conditions are quite generally known. It is also known that any unbalancing of the applied voltage results in a reduction of maximum torque and output, and in a reduction of efficiency. This reduction also occurs when the constants of the external circuits of the motor, such as starting and control circuits, are unbalanced. In this latter case, the unbalancing of motor terminal voltage is a function of the current or slip. It is proposed to investigate these phenomena in a quantitative manner. For this, the method of symmetrical components is very effective, and a proper understanding of the application of this theory is desirable.

The method outlined is quite general in its application, its utility being limited only by the tedious algebra involved. It does not take into account the effect of unsymmetrical windings, or the modifications introduced by slot ratios, such considerations being outside the scope of this paper. It could be applied to squirrel cage machines by using an equivalent 3 phase network for the rotor circuit.

## FREQUENCY OF REACTIONS IN INDUCTION MOTORS

It has been shown that when an unbalanced 3 phase voltage is applied to a 3-phase symmetrical distributed induction-motor winding, currents of positive phase sequence $I_{P1}$ and of negative phase sequence $I_{P2}$ flow in the winding. The currents of positive phase sequence produce a field revolving in the opposite direction to the field produced by the negative phase sequence currents.

If an unbalanced voltage of frequency $\omega_0/2\pi$ be applied to an induction motor the rotor of which is revolving at a velocity of $\omega_0-\omega_1$ electrical radians per second, the positive rotational field produced by the currents $I_{P1}$ in the primary winding will cut the rotor at the angular velocity $\omega_1$, and consequently induce rotor currents of frequency $\omega_1/2\pi$. It will be shown later that when the constants of the rotor circuit are balanced, the rotor currents $I_S$ of frequency $\omega_1/2\pi$ are balanced; but if the constants be unbalanced, these currents will be unbalanced and may be resolved into the components $I_{S1}$ and $I_{S2}$ having the rotor frequency $\omega_1/2\pi$. Component $I_{S1}$ produces a magnetomotive force that revolves in the same direction as the rotor at a velocity $\omega_1$ relative to it, and hence at a velocity $\omega_1 + \omega_0 - \omega_1 = \omega_0$ relative to the stator; that is, it is in step with the stator magnetomotive force produced by $I_{P1}$. But $I_{S2}$ exerts a magnetomotive force revolving at velocity $-\omega_1$ relative to the rotor, and hence at velocity $-\omega_1 + (\omega_0 - \omega_1) = \omega_0 - 2\omega_1$ relative to the stator.

Now, coming back to $I_{P2}$: the magnetomotive force it exerts revolves at velocity $-\omega_0$ relative to the stator, and hence at velocity $-\omega_0 - (\omega_0 - \omega_1) = -(2\omega_0 - \omega_1)$ relative to the rotor. Thus, currents of frequency $(2\omega_0 - \omega_1)/2\pi$ are produced in the rotor, which may be unbalanced, thus causing further reflections, limited only by the higher frequencies. Currents of frequency higher than $(2\omega_0 - \omega_1)/2\pi$ will not be considered, since they will be of negligible amplitude because of the higher reactances offered by the windings to them.

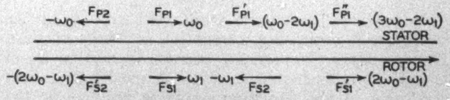

**Fig. 1. Directions and relative velocities of the various magnetomotive forces in an induction motor to which an unbalanced voltage of frequency $\omega_0/2\pi$ is applied**

It may be useful to tabulate the relations between the current reactions, in order to be able to correlate them more readily when writing the equations to determine the performance of the motor; this has been done in table I. In figure 1 the directions and relative velocities of the various magnetomotive forces are shown. Tabulating the reaction frequencies for the currents considered (those of fre-

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[*] Now with Peterson and Cowan Elevator Co. Ltd., Vancouver, B. C.

**Table I—Relations Between Current Reactions in an Induction Motor to Which an Unbalanced Voltage of Frequency $\omega_0/2\pi$ Is Applied**

| Current | Frequency | Velocity of Corresponding Magnetomotive Force: Relative to Stator | Velocity of Corresponding Magnetomotive Force: Relative to Rotor |
|---|---|---|---|
| $I_{P1}$ | $\frac{\omega_0}{2\pi}$ | $+\omega_0$ | $+\omega_1$ |
| $I_{P2}$ | | $-\omega_0$ | $-(2\omega_0 - \omega_1)$ |
| $I_{S1}$ | $\frac{\omega_1}{2\pi}$ | $+\omega_0$ | $+\omega_1$ |
| $I_{S2}$ | | $+(\omega_0 - 2\omega_1)$ | $-\omega_1$ |
| $I_{P1}'$ | $\frac{\omega_0 - 2\omega_1}{2\pi}$ | $+\omega_0 - 2\omega_1$ | $-\omega_1$ |
| $I_{P2}'$ | | $-(\omega_0 - 2\omega_1)$ | $-(2\omega_0 - 3\omega_1)$ |
| $I_{S1}'$ | $\frac{2\omega_0 - \omega_1}{2\pi}$ | $+3\omega_0 - 2\omega_1$ | $-2\omega_0 - \omega_1$ |
| $I_{S2}'$ | | $-\omega_0$ | $-(2\omega_0 - \omega_1)$ |

quency not exceeding $2\omega_0 - \omega_1$), table II is obtained. By way of illustration, the frequency of reaction of $I_{P1}$ on $I_{S1}$ is given in the third row down in the left-hand column. Blank spaces indicate no reaction; for example, there is no reaction of $I_{P2}$ on $I_{P1}$. The oscillograms of rotor currents shown in figures 2 to 4 indicate clearly how the rotor currents are affected by unbalanced conditions. Figure 2 is for balanced applied voltage and balanced stator and rotor circuits. There is a small ripple caused by tooth harmonics, but otherwise the current $I_{S1}$ is the only one present in the rotor.

In figure 3, the stator circuit has been unbalanced by added external resistance. This introduces current $I_S'$ of frequency $\omega'/2\pi$, in the rotor, which has the same amplitude in all 3 phases as has $I_S$; that is, the rotor currents are balanced, and the only component of $I_S'$ is $I_{S2}'$, and of $I_S$, $I_{S1}$.

In figure 4, the rotor circuit, as well as the stator has been unbalanced by added external resistance, with the result that the rotor currents are unbalanced, $I_{S1}$, $I_{S2}$, $I_{S1}'$, and $I_{S2}'$ all being present.

It may seem that $I_{S2}'$ is designated wrongly by the subscript 2, indicating a negative sequence current. In this paper, however, a current is said to be of negative phase sequence when it produces a field revolving in the direction opposite to that of the rotor. Hence, when $I_S'$ is balanced, $I_{S1}'$ is absent.

## General Theory for Unbalanced Conditions

The foregoing considerations permit a mathematical analysis to be undertaken. The problem is one of a symmetrically constructed induction motor having unbalanced constants in stator and rotor circuits, and having an unbalanced voltage supply. Writing the voltage equations for the stator and rotor circuits, using the principles of the theory of symmetrical components and referring to table II if necessary, and taking line-to-neutral values:

$$E_{P1} = R_{P0}I_{P1} + R_{P2}I_{P2} + j\omega_0(L_{P0}I_{P1} + L_{P2}I_{P2} + MI_{S1}) \quad (1)$$

$$E_{P2} = R_{P1}I_{P1} + R_{P0}I_{P2} + j\omega_0(L_{P1}I_{P1} + L_{P0}I_{P2} + MI_{S2}') \quad (2)$$

$$E_{S1} = R_{S0}I_{S1} + R_{S2}I_{S2} + j\omega_1(L_{S0}I_{S1} + L_{S2}I_{S2} + MI_{P1}) = 0 \quad (3)$$

$$E_{S2} = R_{S1}I_{S1} + R_{S0}I_{S2} + j\omega_1(L_{S1}I_{S1} + L_{S0}I_{S2} + 0) = 0 \quad (4)$$

$$E_{S1}' = R_{S0}I_{S1}' + R_{S2}I_{S2}' + j\omega'(L_{S0}I_{S1}' + L_{S2}I_{S2}' + 0) = 0 \quad (5)$$

$$E_{S2}' = R_{S1}I_{S1}' + R_{S0}I_{S2}' + j\omega'(L_{S1}I_{S1}' + L_{S0}I_{S2}' + MI_{P2}) = 0 \quad (6)$$

There is no mutual inductance term in equations 4 and 5, as may be seen by reference to table II. Multiply equation 1 by $\bar{I}_{P1}/\omega_0$, 2 by $\bar{I}_{P2}/\omega_0$, 3 by $\bar{I}_{S1}/\omega_0$, 4 by $\bar{I}_{S2}/\omega_0$, 5 by $\bar{I}_{S1}'/\omega_0$, and 6 by $\bar{I}_{S2}'/\omega_0$. The results are:

$$\frac{E_{P1}\bar{I}_{P1}}{\omega_0} = \frac{R_{P1}I_{P1}\bar{I}_{P1}}{\omega_0} + \frac{R_{P0}I_{P2}\bar{I}_{P1}}{\omega_0} + j(L_{P0}I_{P1}\bar{I}_{P1} + L_{P2}I_{P2}\bar{I}_{P1} + MI_{S1}\bar{I}_{P1}) \quad (7)$$

$$\frac{E_{P2}\bar{I}_{P2}}{\omega_0} = \frac{R_{P1}I_{P1}\bar{I}_{P2}}{\omega_0} + \frac{R_{P0}I_{P2}\bar{I}_{P2}}{\omega_0} + j(L_{P1}I_{P1}\bar{I}_{P2} + L_{P0}I_{P2}\bar{I}_{P2} + MI'_{S2}\bar{I}_{P2}) \quad (8)$$

$$0 = \frac{R_{S1}I_{S1}\bar{I}_{S1}}{\omega_1} + \frac{R_{S0}I_{S2}\bar{I}_{S1}}{\omega_1} + j(L_{S2}I_{S2}\bar{I}_{S1} + L_{S2}I_{S2}\bar{I}_{S1} + MI_{P1}\bar{I}_{S1}) \quad (9)$$

$$0 = \frac{R_{S1}I_{S1}\bar{I}_{S2}}{\omega_1} + \frac{R_{S0}I_{S2}\bar{I}_{S2}}{\omega_1} + j(L_{S1}I_{S1}\bar{I}_{S2} + L_{S0}I_{S2}\bar{I}_{S2} + 0) \quad (10)$$

$$0 = \frac{R_{S0}I_{S1}'\bar{I}_{S1}'}{\omega'} + \frac{R_{S2}I_{S2}'\bar{I}_{S1}'}{\omega'} + j(L_{S0}I_{S1}'\bar{I}_{S1}' + L_{S2}I_{S2}'\bar{I}_{S1}' + 0) \quad (11)$$

$$0 = \frac{R_{S1}I_{S1}'\bar{I}_{S2}'}{\omega'} + \frac{R_{S0}I_{S2}\bar{I}_{S2}'}{\omega'} + j(L_{S1}I_{S1}\bar{I}_{S2}' + L_{S0}I_{S2}'\bar{I}_{S2}' + MI_{P2}\bar{I}_{S2}') \quad (12)$$

**Table II—Reaction Frequencies for Currents of Table I**

| | $I_{P1}$ | $I_{P2}$ | $I_{S1}$ | $I_{S2}$ | $I_{S1}'$ | $I_{S2}'$ |
|---|---|---|---|---|---|---|
| $I_{P1}$ | $\frac{\omega_0}{2\pi}$ | | $\frac{\omega_0}{2\pi}$ | | | |
| $I_{P2}$ | | $\frac{\omega_0}{2\pi}$ | | | | $\frac{\omega_0}{2\pi}$ |
| $I_{S1}$ | $\frac{\omega_1}{2\pi}$ | | $\frac{\omega_1}{2\pi}$ | | | |
| $I_{S2}$ | | | | $\frac{\omega_1}{2\pi}$ | | |
| $I_{S1}'$ | | | | | $\frac{\omega'}{2\pi}$ | |
| $I_{S2}'$ | | $\frac{\omega'}{2\pi}$ | | | | $\frac{\omega'}{2\pi}$ |

Adding equations 16 to 21 inclusive,

$$\frac{E_{P1}\bar{I}_{P1}}{\omega_0} + \frac{E_{P2}\bar{I}_{P2}}{\omega_0} = P + jQ \quad (13)$$

Here

$$Q = (L_{P0}I_{P1}\bar{I}_{P1}) + (L_{P0}I_{P2}\bar{I}_{P2}) + (L_{S0}I_{S1}\bar{I}_{S1}) + (L_{S0}I_{S2}\bar{I}_{S2}) + (L_{S0}I_{S2}'\bar{I}_{S2}') + (L_{S0}I_{S1}\bar{I}_{S1}) + (L_{P1}I_{P1}\bar{I}_{P2} + L_{P2}I_{P2}\bar{I}_{P1}) + (L_{S1}I_{S1}\bar{I}_{S2} + L_{S2}I_{S2}\bar{I}_{S1}) + (L_{S1}I_{S1}'\bar{I}_{S2}' + L_{S2}I_{S2}'\bar{I}_{S1}') + (L_{S2}I_{S2}'\bar{I}_{S1}' + L_{S1}I_{S1}'\bar{I}_{S2}') + M(I_{S1}\bar{I}_{P1} + I_{P1}\bar{I}_{S1}) + M(I_{S2}'\bar{I}_{P2} + I_{P2}\bar{I}_{S2}') \quad (14)$$

The sum in each pair of parentheses is real, since each sum is of the form $A\bar{A}$ or $A\bar{B} + B\bar{A}$, each of which is real. Therefore $Q$ is real and $jQ$ imaginary—the reactive volt-ampere input to the motor.

$$P = \frac{1}{\omega_0}\left(R_{P0}I_{P1}\bar{I}_{P1} + R_{P0}I_{P2}\bar{I}_{P2} + R_{P1}I_{P1}\bar{I}_{P2} + R_{P2}I_{P2}\bar{I}_{P1}\right) + \frac{1}{\omega_1}\left(R_{S0}I_{S1}\bar{I}_{S1} + R_{S0}I_{S2}\bar{I}_{S2} + R_{S1}I_{S1}\bar{I}_{S2} + R_{S2}I_{S2}\bar{I}_{S1}\right) + \frac{1}{\omega'}\left(R_{S0}I_{S1}'\bar{I}_{S1}' + R_{S0}I_{S2}'\bar{I}_{S2}' + R_{S1}I_{S1}'\bar{I}_{S2}' + R_{S2}I_{S2}\bar{I}_{S1}'\right) \quad (15)$$

and this also is real—the watts input to the motor divided by $\omega_0$, from equation 13.

The copper loss in the primary circuit is

$$R_{P0}I_{P1}\bar{I}_{P1} + R_{P0}I_{P2}\bar{I}_{P2} + R_{P1}I_{P1}\bar{I}_{P2} + R_{P2}I_{P2}\bar{I}_{P1} = l_P$$

and similar expressions hold for the copper losses in the secondary circuit caused by currents $I_{S1}$, $I_{S2}$, and $I_{S1}'$, $I_{S2}'$. The output of the motor is, per phase,

$$\begin{aligned} W &= (\text{input}) - (\text{copper losses}) \\ &= \omega_0 P \quad - (\text{copper losses}) \end{aligned}$$

neglecting the iron losses. Thus,

$$\begin{aligned} W = {} & \left(\frac{\omega_0}{\omega_1} - 1\right)\left(R_{S0}I_{S1}\bar{I}_{S1} + R_{S0}I_{S2}\bar{I}_{S2} + R_{S1}I_{S1}\bar{I}_{S2} + R_{S2}I_{S2}\bar{I}_{S1}\right) + \\ & \left(\frac{\omega_0}{\omega'} - 1\right)\left(R_{S0}I_{S1}'\bar{I}_{S1}' + R_{S0}I_{S2}'\bar{I}_{S2}' + R_{S1}I_{S1}'\bar{I}_{S2}' + R_{S2}I_{S2}'\bar{I}_{S1}'\right) \quad (16) \\ = {} & \frac{\omega_0 - \omega_1}{\omega_1}\, l_S - \frac{\omega_0 - \omega'}{\omega'}\, l_S' \quad (17) \end{aligned}$$

In equation 17, $\frac{\omega_0 - \omega'}{2\omega_0 - \omega_1}$ is positive for all motor speeds from synchronism to standstill. Therefore the quantity $\frac{\omega_0 - \omega'}{2\omega_0 - \omega'}$, $l_S'$ is the power fed back into the supply circuit. This power is drawn from the line through the positive sequence component. The torque in pound-feet is given by

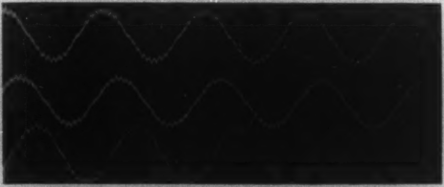

**Fig. 2. Rotor currents in an induction motor with balanced stator and rotor circuits and balanced applied voltage; slip = 0.267**

A 60 cycle timing wave may be seen at the bottom

$$\begin{aligned} T &= \frac{33{,}000\pi p W}{746(2\pi)(60)(\omega_0 - \omega_1)} \\ &= \frac{0.369 p W}{(\omega_0 - \omega_1)} \\ &= 0.369 p \left(\frac{l_S}{\omega_1} - \frac{l_S'}{\omega'}\right) \quad (18) \end{aligned}$$

This is a more general statement of the well-known law for the torque of induction motors under balanced conditions: "Torque is proportional to rotor copper loss divided by the slip." Equation 18 states that the torque is proportional to

$$\frac{\text{positive sequence losses}}{\text{corresponding slip}} - \frac{\text{negative sequence losses}}{\text{corresponding slip}}$$

If the form of the torque-slip curve is desired, equations 1 to 6 must be solved for the several currents, and their values substituted in equation 18.

The solution for the general case is given in appendix I. The solution for a given condition may be obtained from these equations. In what follows, simplifications introduced by special conditions are considered. Here, the fundamental equations 1 to 6 are taken as the starting point, but the same results could be obtained from the general solution.

**Fig. 3. Rotor currents in an induction motor with unbalanced stator circuit, balanced rotor circuit, and balanced applied voltage; slip = 0.05**

A 60 cycle timing wave may be seen at the bottom

### BALANCED APPLIED VOLTAGE; ALL IMPEDANCES BALANCED

In this case, $E_{P2} = R_{P1} = R_{P2} = R_{S1} = R_{S2} = L_{P1} = L_{P2} = L_{S1} = L_{S2} = 0$, and the 6 fundamental equations reduced to

$$\begin{aligned} E_{P1} &= R_{P0}I_{P1} + j\omega_0(L_{P0}I_{P1} + MI_{S1}) && (19) \\ E_{P2} &= 0 = R_{P0}I_{P2} + j\omega_0(L_{P0}I_{P2} + MI_{S2}') && (20) \\ E_{S1} &= 0 = R_{S0}I_{S1} + j\omega_1(L_{S0}I_{S1} + MI_{P1}) && (21) \\ E_{S2} &= 0 = R_{S0}I_{S2} + j\omega_1(L_{S0}I_{S2} + 0) && (22) \\ E_{S1}' &= 0 = R_{S0}I_{S1}' + j\omega'(L_{S0}I_{S1}' + 0) && (23) \\ E_{S2}' &= 0 = R_{S0}I_{S2}' + j\omega'(L_{S0}I_{S2}' + MI_{P2}) && (24) \end{aligned}$$

From equation 22 $I_{S2} = 0$, and from 23 $I_{S1}' = 0$. Combining equations 20 and 24 it is found that $I_{P2} = 0$ and $I_{S2}' = 0$. Therefore, in equations 20, 22, 23, and 24, every term is zero, leaving equations 19 and 21 for consideration. Multiplying equation 19 by $\bar{I}_{P1}/\omega_0$ and 21 by $\bar{I}_{S1}/\omega_0$, and adding the 2 equations so formed,

$$\frac{E_{P1}\bar{I}_{P1}}{\omega_0} = \frac{R_{P0}I_{P1}'\bar{I}_{P1}}{\omega_0} + \frac{R_{S0}I_{S1}\bar{I}_{S1}}{\omega_0} + j[L_{P0}I_{P1}\bar{I}_{P1} + L_{S0}I_{S1}\bar{I}_{S1} + M(I_{S1}\bar{I}_{P1} + I_{P1}\bar{I}_{S1})] \quad (25)$$

whence the real power input to the motor is

$$R_{P0}I_{P1}\bar{I}_{P1} + \frac{\omega_0}{\omega_1} R_{S0}I_{S1}\bar{I}_{S1} \quad (26)$$

The total copper losses are $R_{P0}I_{P1}\bar{I}_{P1} + R_{S0}I_{S1}\bar{I}_{S1}$.

**Fig. 4. Rotor currents in an induction motor with unbalanced stator and rotor circuits, and with balanced applied voltage; slip = 0.0565**

A 60 cycle timing wave may be seen at the bottom

Subtracting these from the input, the output is found to be

$$W_1 = \left(\frac{\omega_0}{\omega_1} - 1\right) R_{S0} I_{S1} \bar{I}_{S1} \tag{27}$$

and the torque is

$$T_1 = \frac{0.369pW_1}{\omega_0 - \omega_1} = 0.369p \frac{R_{S0} I_{S1} \bar{I}_{S1}}{\omega_1} \tag{28}$$

Solving equations 19 and 21 for $I_{S1}$,

$$I_{S1} = \frac{-j\omega_1 M E_{P1}}{R_{P0} - \omega_0 \omega_1 M^2 + j\omega_0 L_{P0}} = E_{P1}(a + jb)$$

Hence $I_{S1} = E_{P1}(a - jb)$, and $I_{S1}\bar{I}_{S1} = E_{P1}^2(a^2 + b^2)$, where $a$ and $b$ are functions of the motor constants and the slip.

### Unbalanced Applied Voltage; All Impedances Balanced

In this case, equations 19 to 24 apply, with the exception that $E_{P2}$ has a value in equation 20; $I_{S2} = 0$ and $I_{S1}' = 0$, but $I_{P2}$ and $I_{S2}'$ are not zero. From equations 19 and 21, values are obtained for positive power and torque given by equations 27 and 28; but there is, in this case, a negative term also in the power and torque equations, for, from equations 20 and 24, the real part of $E_{P2}\bar{I}_{P2}$ is

$$(E_{P2}\bar{I}_{P2})_{\text{real}} = R_{P0} I_{P2} \bar{I}_{P2} + \frac{\omega_0}{\omega'} R_{S0} I_{S2}' \bar{I}_{S2}' \tag{29}$$

The copper losses are, for the negative sequence components of current, $R_{P0} I_{P2} \bar{I}_{P2} + R_{S0} I_{S2}' \bar{I}_{S2}'$. Subtracting these losses from the input,

$$W_2 = \left(\frac{\omega_0}{\omega'} - 1\right) R_{S0} I_{S2}' \bar{I}_{S2}'$$

$$= -\frac{\omega_0 - \omega_1}{\omega'} R_{S0} I_{S2}' \bar{I}_{S2}' \tag{30}$$

as the negative mechanical power. The complete expression for mechanical power is

$$W = W_1 + W_2 = (\omega_0 - \omega_1)\left(\frac{R_{S0} I_{S1} \bar{I}_{S1}}{\omega_1} - \frac{R_{S0} I_{S2}' \bar{I}_{S2}'}{\omega'}\right) \tag{31}$$

and

$$T = 0.369p\left(\frac{R_{S0} I_{S1} \bar{I}_{S1}}{\omega_1} - \frac{R_{S0} I_{S2}' \bar{I}_{S2}'}{\omega'}\right) \tag{32}$$

As pointed out before, the negative sign in equation 31 indicates that power is being fed back into the supply circuit. Since the negative sequence does work to feed power back to the supply, the motor functions as a phase balancer and as a means of supplying mechanical power simultaneously.

In the equation for torque (32), $I_{S2}'$ may be determined from equations 20 and 24; $I_{S1}$ was given as $E_{P1}(a + jb)$. From equations 20 and 24, $I_{S2} = E_{P2}(g + jf)$. Therefore, since

$$I_{S1}\bar{I}_{S1} = E_{P1}^2(a^2 + b^2) \text{ and } I_{S2}'\bar{I}_{S2}' = E_{P2}^2(g^2 + f^2)$$

then

$$T_1 = E_{P1}^2 f(s, c) \text{ and } T_2 = E_{P2}^2 f[(2 - s), c]$$

where $s$ and $c$ represent slip and motor constants, respectively. It is evident from these expressions for $T_1$ and $T_2$ that, in general, $T_1/T_2$ is not equal to $E_{P1}^2/E_{P2}^2$, although this is true at standstill.

The curves in figure 5 illustrate the foregoing clearly. They show $T_1$ for positive sequence voltage $E_{P1}$, and $T_2$ for negative sequence voltage $E_{P2}$. Curve, $T_{SP}$, is for the case in which $E_{P2} = -E_{P1}$, so that

$$E_{0A} = (E_{P1} - E_{P1}) = 0, \quad E_{0B} = (-0.5 - j0.866)E_{P1} + (-0.5 + j0.866)(-E_{P1}) = -j1.732E_{P1},$$

$$E_{0C} = (-0.5 + j0.866)E_{P1} - (-0.5 - j0.866)(-E_{P1}) = +j1.732E_{P1}.$$

That is, $E_{0B} = -E_{0C}$, corresponding to a single phase voltage $2E_{P1}$ applied between terminals $B$ and $C$. The curve is, of course, of the form usually shown for single phase operation. These curves were calculated from tests on a 3 phase motor; the calculations are shown in a later section.

It may be observed that any unbalancing of applied voltage has a more serious effect on the starting torque than on the pull-out torque. This fact is illustrated by the curves of figure 6 calculated for the same motor. It is evident also, that if alternating current were used for braking purposes, the

**Table III—Results of Blocked Torque Tests**

| Volts Applied | External Line Resistance, Ohms | Primary Impedance Components, Ohms | Current in Secondary, Amperes | | Torque, Pound-Feet | |
|---|---|---|---|---|---|---|
| | | | $I_{S1}$ | $I_{S2}$ | Calculated | Observed |
| 62 | A 2.03 | $Z_{P0} = 1.5 + j11.1$ | 28.4 | 10.00 | 3.42 | 3.25 |
| | B 2.03 | $Z_{P1} = 0.34 + j\,0.58$ | | | | |
| | C 0.0 | $Z_{P2} = 0.34 - j\,0.58$ | | | | |
| 62.3 | A 1.37 | $Z_{P0} = 1.12 + j11.1$ | 30.9 | 5.54 | 4.48 | 4.62 |
| | B 1.55 | $Z_{P1} = 0.2 + j\,0.45$ | | | | |
| | C 0.0 | $Z_{P2} = 0.2 - j\,0.45$ | | | | |
| 61.8 | A 0.85 | $Z_{P0} = 0.73 + j11.1$ | 33.2 | 3.72 | 5.27 | 5.9 |
| | B 0.91 | $Z_{P1} = 0.13 + j\,0.26$ | | | | |
| | C 0.0 | $Z_{P2} = 0.13 - j\,0.26$ | | | | |
| 126 | A 0.85 | $Z_{P0} = 4.5 + j11.1$ | 31.2 | 13.1 | 3.98 | 3.23 |
| | B 0.91 | $Z_{P1} = 1.0 + j\,1.93$ | | | | |
| | C 0.0 | $Z_{P2} = 1.0 - j\,1.93$ | | | | |
| 126 | A 4.78 | $Z_{P0} = 3.52 + j11.1$ | 37.5 | 13.7 | 5.9 | 5.5 |
| | B 5.34 | $Z_{P1} = 0.7 + j\,1.54$ | | | | |
| | C 0.0 | $Z_{P2} = 0.7 - j\,1.54$ | | | | |
| 114 | A 3.22 | $Z_{P0} = 2.34 + j11.1$ | 43.2 | 13.7 | 8.13 | 7.78 |
| | B 3.37 | $Z_{P1} = 0.51 + j\,1.0$ | | | | |
| | C 0.0 | $Z_{P2} = 0.51 - j\,1.0$ | | | | |

results might be far from satisfactory if the applied voltage were unbalanced.

The increased heating of the motor on load is a more important consideration than the torque reduction. The value of the negative sequence current flowing can be obtained by multiplying the negative sequence voltage by the standstill admittance (considered constant over the motor speed range to negative sequence currents). Full voltage impressed on motors of normal design when locked will cause 6 to 8 times full load current to flow; that is, they have an admittance of 6 to 8 at 100 per cent slip. If these motors were to have unbalanced voltages impressed on them such that the negative sequence component of voltage amounted to about 15 per cent of the positive sequence component (that is, an unbalance factor of 0.15) there would result a negative sequence current equal to full load current. Thus, on load, the torque of ordinary induction motors is not sensitive to a moderate degree of voltage unbalance, but their heating characteristics are very sensitive to such unbalance.

### UNBALANCED APPLIED VOLTAGE; PRIMARY IMPEDANCES UNBALANCED; SECONDARY IMPEDANCES BALANCED

Referring to equations 1 to 6, in which $R_{S1}$, $R_{S2}$, $L_{S1}$, and $L_{S2}$ will be zero for this case, it may be noted that $I_{S2} = 0$ from equation 4 and that $I_{S1}' = 0$ from equation 5. That is, the only currents in the rotor are $I_{S1}$ and $I_{S2}'$; or, in other words, the rotor currents are balanced, but, in general, have different frequencies. The torque is given by equation 18 where $I_{S2} = I_{S1}' = 0$; that is,

$$T = 0.369p\left[\frac{R_{S0}I_{S1}I_{S1}}{\omega_1} - \frac{R_{S0}I_{S2}'I_{S2}'}{\omega'}\right] \tag{33}$$

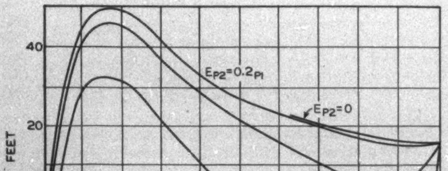

**Fig. 5. Torque-slip curves for an induction machine, showing the effect of unbalanced voltage on a balanced machine**

It is worthy of notice that $I_{S1}$ is no longer a function of $E_{P1}$, $s$, and $c$ only, but also of $E_{P2}$; similarly, $I_{S2}'$ is now a function of $E_{P1}$, as well as of $E_{P2}$, $s$, and $c$. This may be seen from equations 1 to 6, for, writing the necessary equations in the following form,

$$E_{P1} = Z_{P0}I_{P1} + Z_{P2}I_{P2} - M_0I_{S1} + 0 \tag{34}$$

$$E_{P2} = Z_{P1}I_{P1} + Z_{P0}I_{P2} + 0 - M'I_{S2}' \tag{35}$$

$$0 = -M_1I_{P1} + 0 + Z_SI_{S1} + 0 \tag{36}$$

$$0 = 0 - M'I_{P2} + 0 + Z_S'I_{S2}' \tag{37}$$

where

$$Z_{P0} = R_{P0} + j\omega_0L_{P0},\quad Z_{P1} = R_{P1} + j\omega_0L_{P1},$$
$$Z_{P2} = R_{P2} + j\omega_0L_{P2},\quad Z_S = R_S + j\omega_1L_S,\quad Z'_S = R_S + j\omega'L_S,$$
$$M_0 = -j\omega_0M,\quad M_1 = -\,j\omega_1M,\quad \text{and}\quad M' = -\,j\omega'M$$

there results

$$I_{S1} = \frac{\begin{vmatrix} Z_{P0} & Z_{P2} & E_{P1} & 0 \\ Z_{P1} & Z_{P0} & E_{P2} & -M_0 \\ -M_1 & 0 & 0 & 0 \\ 0 & -M' & 0 & Z_S' \end{vmatrix}}{\Delta} \quad \text{and} \quad I_{S2}' = \frac{\begin{vmatrix} Z_{P0} & Z_{P2} & -M_0 & E_{P1} \\ Z_{P1} & Z_{P0} & 0 & E_{P2} \\ -M_1 & 0 & Z_S & 0 \\ 0 & -M' & 0 & 0 \end{vmatrix}}{\Delta} \tag{38}$$

where

$$\Delta = \begin{vmatrix} Z_{P0} & Z_{P2} & -M_0 & 0 \\ Z_{P1} & Z_{P0} & 0 & -M' \\ -M_1 & 0 & Z_S & 0 \\ 0 & -M' & 0 & Z_S' \end{vmatrix}$$

Evaluating,

$$I_{S1} = \frac{-E_{P1}M_1(M_0M' - Z_{P0}Z_S') - E_{P2}M_1Z_{P2}Z_S'}{(M_0M' - Z_{P0}Z_S')(M_0M_1 - Z_{P0}Z_S) - Z_{P1}Z_{P2}Z_SZ_S'} \tag{39}$$

$$I_{S2}' = \frac{-E_{P1}M'Z_{P1}Z_S - E_{P2}M'(M_0M_1 - Z_{P0}Z_S)}{(M_0M' - Z_{P0}Z_S')(M_0M_1 - Z_{P0}Z_S) - Z_{P1}Z_{P2}Z_SZ_S'} \tag{40}$$

This is in agreement with the statement commonly made in treatises on symmetrical components, that: for a balanced network, an applied voltage of one sequence will produce current of that sequence only, but for an unbalanced network, in general, a voltage component of either sequence will give rise to current components of both sequences.

### UNBALANCED APPLIED VOLTAGE; PRIMARY IMPEDANCES BALANCED; SECONDARY IMPEDANCES UNBALANCED

In this case $R_{P1} = R_{P2} = L_{P1} = L_{P2} = 0$. From equations 1 to 6, it may be seen that currents $I_{P1}$, $I_{P2}$, $I_{S1}$, $I_{S2}$, $I_{S1}'$, $I_{S2}'$ all have values, and the torque is given by the general equation 18.

It should be noted that the torque spoken of is, in all cases, the effective value. In reality, the torque is pulsating whenever the rotor currents are unbalanced, that is, whenever the rotor constants are unbalanced. One may think of a component of single phase torque, caused by unbalance, in this connection. The motor, furthermore, will not be as quiet when the secondary currents are unbalanced as it will when they are balanced. There is a gradual increase in the intensity of the hum, from the condition of perfect balance to that in which one phase of the rotor is open-circuited.

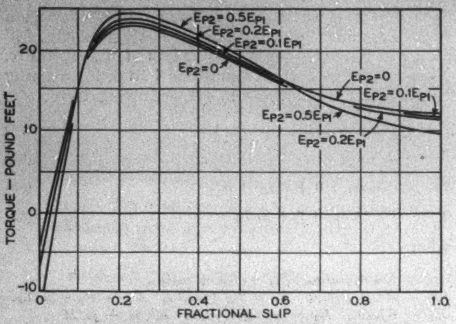

**Fig. 6. Torque-slip curves for an induction motor, showing effect of unbalanced voltage on a motor with unbalanced primary circuit**

### BLOCKED TORQUE TESTS

These tests were carried out on a 10-horsepower 60-cycle 6-pole wound-rotor induction motor, having a delta-connected primary and star-connected secondary. The constants, reduced to equivalent line-to-neutral values, were

$$R_P = 0.146 \qquad R_S = 0.275$$
$$\omega_0 L_P = 11.1 \qquad \omega_0 L_S = 4.67$$
$$\omega_0 M = 6.45 \qquad (\omega_0 = 377)$$

Blocked torque tests were made with balanced voltage applied and the primary circuit unbalanced by added resistance. The currents were calculated from equations 39 and 40, which, for standstill and balanced applied voltage, reduce to

$$I_{S1} = \frac{-E_{P1}M_0}{(M_0M_1 - Z_{P0}Z_S) - Z_{P1}Z_{P2}Z_SZ_S'}$$

$$I_{S2}' = \frac{-E_{P1}M_0Z_{P1}Z_S}{(M_0M_1 - Z_{P0}Z_S) - Z_{P1}Z_{P2}Z_SZ_S'}$$

The results are shown in table III. The observed and calculated values for torque are in fairly close agreement. The neglect of iron losses tends to make the calculated values high, but this is compensated to some extent by the saturation at higher voltages, which makes the actual currents greater than those calculated.

### CALCULATIONS FOR SLIP-TORQUE CURVES FOR BALANCED MOTOR; UNBALANCED APPLIED VOLTAGE

In this case equations 39 and 40 reduce to

$$I_{S1} = \frac{-M_1E_{P1}}{M_0M_1 - Z_{P0}Z_S} \qquad I_{S2}' = \frac{-M'E_{P2}}{M_0M_1 - Z_{P0}Z_S}$$

which become, for the particular motor under consideration

$$I_{S1} = \frac{0.62\underline{/266^\circ 15'}s\,E_{P1}}{0.293\underline{/266^\circ 15'} + s} \qquad I_{S2}' = \frac{0.62\underline{/266^\circ 15'}(2-s)}{0.293\underline{/266^\circ 15'} + (2-s)}$$

The data for the curves are:

| s | K | s | K |
|---|---|---|---|
| 0.1 | 18.65 | 1.3 | 13.3 |
| 0.2 | 28.0 | 1.5 | 11.6 |
| 0.3 | 30.0 | 1.7 | 10.3 |
| 0.5 | 26.4 | 1.8 | 9.9 |
| 0.7 | 21.8 | 1.9 | 9.4 |
| 1.0 | 16.6 | | |

K is defined by $T_1 = KE_{P1}^2$

The curves are plotted in figure 5.

### CALCULATIONS FOR SLIP-TORQUE CURVES; UNBALANCED PRIMARY; UNBALANCED APPLIED VOLTAGE

The current and torque values were calculated from equations 39, 40, and 33. The results are as follows:

| s | $I_{S1}$ | $I_{S2}'$ |
|---|---|---|
| 0.0 | 0 | $0.423E - 0.324E$ |
| 0.1 | $0.162E - 0.0455E$ | $0.433E - 0.279E$ |
| 0.2 | $0.245E - 0.071\ E$ | $0.437E - 0.243E$ |
| 0.3 | $0.307E - 0.081\ E$ | $0.432E - 0.217E$ |
| 0.5 | $0.361E - 0.097\ E$ | $0.429E - 0.187E$ |
| 0.7 | $0.386E - 0.102\ E$ | $0.422E - 0.170E$ |
| 1.0 | $0.409E - 0.105\ E$ | $0.409E - 0.105E$ |

The slip-torque curves of figure 6 were obtained by substituting these values in equation 33.

## Appendix I—Fundamental Equations

The fundamental equations may be written in the following form:

$$E_{P1} = Z_{P0}I_{P1} + Z_{P2}I_{P2} - M_0I_{S1} + 0 + 0 + 0 \tag{1a}$$
$$E_{P2} = Z_{P1}I_{P1} + Z_{P0}I_{P2} + 0 + 0 + 0 - M_0I_{S2}' \tag{2a}$$
$$E_{S1} = -M_1I_{P1} + 0 + Z_{S0}I_{S1} + Z_{S2}I_{S2} + 0 + 0 = 0 \tag{3a}$$
$$E_{S2} = 0 + 0 + Z_{S1}I_{S1} + Z_{S0}I_{S2} + 0 + 0 = 0 \tag{4a}$$
$$E_{S1}' = 0 + 0 + 0 + 0 + Z_{S0}'I_{S1}' + Z_{S2}'I_{S2}' = 0 \tag{5a}$$
$$E_{S2}' = 0 - M'I_{P2} + 0 + 0 + Z_{S1}'I_{S1}' + Z_{S0}'I_{S2}' = 0 \tag{6a}$$

where

$$Z_{P0} = R_{P0} + j\omega_0L_{P0} \qquad Z_{S0}' = R_{S0}' + j\omega'L_{S0}$$
$$Z_{P1} = R_{P1} + j\omega_0L_{P1} \qquad Z_{S1}' = R_{S1}' + j\omega'L_{S1}$$
$$Z_{P2} = R_{P2} + j\omega_0L_{P2} \qquad Z_{S2}' = R_{S2}' + j\omega'L_{S2}$$
$$Z_{S0} = R_{S0} + j\omega_1L_{S0} \qquad M_0 = -j\omega_0M$$
$$Z_{S1} = R_{S1} + j\omega_1L_{S1} \qquad M_1 = -j\omega_1M$$
$$Z_{S2} = R_{S2} + j\omega_1L_{S2} \qquad M' = -j\omega'M$$

Solving by determinants for the currents:

$$\Delta I_{P1} = E_{P1}S(Z_{P0}S' - Z_{S0}'M_0M') - E_{P2}Z_{P2}SS'$$
$$\Delta I_{P2} = -E_{P1}S(Z_{P1}S' - Z_{S0}'M_0M_1) + E_{P2}S'(Z_{P0}S - Z_{S0}M_0M_1)$$
$$\Delta I_{S1} = E_{P1}Z_{S0}M_1(Z_{P0}S' - Z_{S0}'M_0M') - E_{P2}Z_{S0}Z_{P2}M_1S'$$
$$\Delta I_{S2} = -E_{P1}Z_{S1}M_1(Z_{P0}S' - Z_{S0}'M_0M') + E_{P2}Z_{S1}Z_{P2}M_1S'$$
$$\Delta I_{S1}' = E_{P1}Z_{P1}Z_{S2}'M'S - E_{P2}Z_{S2}'M'(Z_{P0}S - Z_{S0}M_0M_1)$$
$$\Delta I_{S2}' = -E_{P1}Z_{P1}Z_{S0}'M'S + E_{P2}Z_{S0}'M'(Z_{P0}S - Z_{S0}M_0M_1)$$

where

$$\Delta = (Z_{P0}S - Z_{S0}M_0M_1)(Z_{P0}S' - Z_{S0}'M_0M') - Z_{P1}Z_{P2}SS'$$
$$S = (Z_{S0}^2 - Z_{S1}Z_{S2}')$$
$$S' = (Z_{S0}'^2 - Z_{S1}'Z_{S2}')$$

## Appendix II—Notation

Unless otherwise indicated, or obvious, notation is as follows:

$E_{P1}$, $E_{P2}$ —Positive and negative sequence components, respectively, of applied voltage

$E_{S1}$, $E_{S2}$ —Positive and negative sequence components of voltage in secondary circuit, of frequency $\omega_1/2\pi$

$E_{S1}'$, $E_{S2}'$ —Positive and negative sequence components of voltage in secondary circuit, of frequency $\omega'/2\pi$ where $\omega' = 2\omega_0 - \omega_1$

$I_{P1}$, $I_{P2}$ —Primary current components of frequency $\omega_0/2\pi$

$I_{S1}$, $I_{S2}$ —Secondary current components of frequency $\omega_1/2\pi$

$I_{P1}$, $I_{P2}$ —Primary current components of frequency $(\omega_0 - 2\omega_1)/2\pi$

$I_{S1}'$, $I_{S2}'$ —Secondary current components of frequency $(2\omega_0 - \omega_1)/2\pi$

$R_{P0}$, $R_{P1}$, $R_{P2}$—Resistance components of primary (including that external to motor)

$R_{S0}$, $R_{S1}$, $R_{S2}$—Resistance components of secondary (including that external to motor)

$L_{P0}$, $L_{P1}$, $L_{P2}$—Self-inductance coefficients components of primary

$L_{S0}$, $L_{S1}$, $L_{S2}$—Self-inductance coefficients components of secondary

$M$ —Coefficient of mutual inductance

$p$ —Number of poles

$3W$ —Total watts output of motor

$3T$ —Torque in pound-feet

$3(P + jQ)$ —Volt-ampere input to motor

$I$, $E$ —The conjugates of $I$, $E$

Equivalent line-to-neutral values are taken for all voltages, currents, and constants.

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# Discussions

## Of A.I.E.E. Papers—as Recommended for Publication by Technical Committees

On this and the following 22 pages appear discussions submitted for publication, and approved by the technical committees, on papers presented at the sessions on electrical machinery, electrochemistry and electrometallurgy, instruments and measurements, and power transmission at the 1936 A.I.E.E. winter convention, New York, N. Y., January 28–31. Other discussion of winter convention papers will be published in later issues. Authors' closures, where they have been submitted, will be found at the end of the discussion on their respective papers.

Members anywhere are encouraged to submit written discussion of any paper published in Electrical Engineering, which discussion will be reviewed by the proper technical committee and considered for possible publication in a subsequent issue. Discussions of papers scheduled for presentation at an A.I.E.E. meeting or convention will be closed 2 weeks after presentation. Discussions should be (1) concise; (2) restricted to the subject of the paper or papers under consideration; and (3) typewritten and submitted in triplicate to C. S. Rich, secretary technical program committee, A.I.E.E. headquarters, 33 West 39th Street, New York, N. Y.

## Lightning Currents in Field and Laboratory

**Discussion and author's closure of a paper by P. L. Bellaschi published in the August 1935 issue, pages 837–43, and presented for oral discussion at the power transmission session of the winter convention, New York, N. Y., January 29, 1936.**

**C. M. Foust** (General Electric Co., Schenectady, N. Y.): The effort of P. L. Bellaschi to assemble examples of the destructive effects of natural lightning is to be commended. Through the comparison of these effects with those produced in the laboratory by surge current and voltage generators, information of substantial value is to be gained. However, only through actual field measurements of lightning currents, voltages, and wave shapes can the gap between field damage and laboratory damage be completely bridged. As the author points out, "the practical method now commonly used to measure lightning currents discharged through the steel towers of transmission lines depends simply on the magnetization of magnetic links and their ability to retain the magnetization thereof." This arrangement is called the surge crest ammeter.

In steel tower applications of this ammeter measurements have been made of lightning currents in tower legs and tower arms, and in addition, measurement stations have been made on overhead ground wires, tower top lightning rods, counterpoise wires (buried ground wires), lightning arrester down leads, and radio masts. A rough summary shows the extent of these measurements obtained to date to be a total of 1,500 records. Among these are 873 tower leg records involving 365 towers and 294 strokes. On tower arms 20 records have been obtained. Altogether 24 records of tower top lightning rod currents and 209 records of counterpoise currents have been collected. Records of 8 strokes involving 2 strokes to radio towers, and 411 records of lightning arrester down-lead surges have been reported. These records have been accumulated from over 5,000 measurement stations.

Current amplitude measurements were shown up to and including 1934 in a paper presented before the Great Lakes section in 1935 "Lightning Investigation on Transmission Lines-V" (Elec. Engg., v. 54, Sept. 1935, p. 934–42). In this connection the writer would like to ask P. L. Bellaschi the basis on which figure 8 of the paper was plotted. Did all 3 curves go through 9 records at 50,000 amperes, or is this point common to all curves because ratio factors were used to reduce each to the same section of the co-ordinate paper. In any event, the writer's records from field measurements indicate somewhat higher stroke currents ranging up to a maximum above 200,000 amperes, with 50 per cent of the strokes at 36,000 amperes. Single tower currents ranged up to 132,000 amperes with a 50 per cent level of 30,000 amperes. A current of 162,000 amperes was measured in a radio tower.

Probably the most valuable feature of the surge crest ammeter method is that current values in all parts of a line structure can be obtained for a single disturbance. When such records are complete the point of contact of the stroke, the distribution of current in the various members of the line structure, and the spreading of current in the ground and counterpoise can be obtained.

**D. D. MacCarthy** (General Electric Co., Pittsfield, Mass.): P. L. Bellaschi mentions the use of a device for measuring lightning currents which depends upon the hole punctured in a piece of paper to give the current magnitude. The size of the hole punctured in the telltale paper is a measure of the spark diameter which is taken as a measure of the current discharged. The author also makes use of the size of the spot burned on the gap plugs of deionizing gaps in determining current magnitudes. It seems probable that the size of the electrode burn is related to the spark diameter in the same way as is the size of the hole punctured in the telltale paper.

In 1933 calibration curves were made in the lightning arrester laboratory of the company with which the writer is connected to relate the area punctured in telltale paper with the magnitude of impulse currents which were measured by the cathode ray oscillograph. The results for copper electrodes are given in figure 1 of this discussion. These data show that while there is in general a correlation between the area of the puncture and current magnitude, the method does not give accurate results. As seen from this figure the magnitude of the current corresponding to an individual puncture may vary by a ratio of 10 to 1.

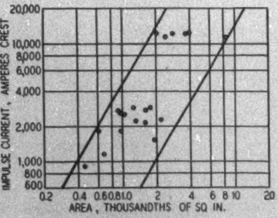

**Fig. 1. Relation of impulse current to area of hole in telltale paper**

Copper electrodes were used

No similar calibration curve published in a scientific paper has come to the writer's attention. A device using telltale paper, however, has been put on the market. The calibration published in the manufacturer's bulletin shows a ratio of 8 or 10 to 1 in current magnitude for a given puncture. No doubt P. L. Bellaschi is familiar with this calibration. It appears probable that the author used a similar calibration curve for correlating the size of the burn on electrodes with the magnitude of the impulse current. Considering the data in the bulletin just referred to, together with those of figure 1 of this discussion, it seems that only very approximate results are obtained when either the punctured paper or burned electrode method is used. It would be of interest if the author would reproduce the calibration curve he used.

It is believed that impulse current magnitude can be measured with an error of the order of 10 per cent by magnetic links. Because of the difference in accuracy and because of other reasons given in K. B. McEachron's discussion of the paper it seems that the agreement between the data of curve *A*, figure 8 of the paper, and that of curves *B* and *C* is largely fortuitous. It would appear that the author does not have sufficient data to establish an average curve, particularly if the method he uses gives a possible variation of 10 to 1 in current measurement.

**K. B. McEachron** (General Electric Co., Pittsfield, Mass.): P. L. Bellaschi has referred to the repetitive or multiple stroke. Much of the data obtained with reference to fusing of wires or the crushing of conductors as a result of the "pinch effect" is doubtful, from the point of view of current magnitude, because the number of strokes involved is not known. Since the time of application is a very important factor in determining the total heating from a current wave of any given crest, it is usually possible only to state an upper limit of the current, while the actual value based on heating or crushing effects will be in considerable doubt. By far the best method of determining the crest value of current will be through the use of some instrument whose registration is not dependent upon the time of application.

Although direct data are lacking it seems very probable that fires are more certain to result from multiple strokes than from single strokes unless explosive gases are involved. Conversely, severe shattering, without burning of wooden objects which are inflammable, is probably due to single strokes of large current magnitude.

There is, of course, plenty of evidence to show that the wind may blow the ionized path of a lightning discharge along so that succeeding discharges are displaced. A wind velocity of 45 miles per hour corresponds to 66 feet per second. Probably the shortest interval of time between successive strokes reported to date is 0.0026 second (see "Photographing Lightning with Movie Camera," A. Larsen, *Sci. Am. Supplement*, 1907, p. 26200–202) and the longest is 0.16 second (see "Multiple Lightning Strokes," K. B. McEachron, Elec. Engg., v. 53, Dec. 1934, p. 1633–37). Thus, the present known limits of distance are from 0.17 feet to 10.5 feet with a 45 mile per hour wind. It seems, therefore, that if the first stroke contacted a line or ground wire, succeeding strokes would probably do the same, but the discharge might shift from conductor to conductor or from ground wire to line conductor. The results outlined in the writer's paper, just referred to, show clearly that more than one phase may be involved successively in a multiple stroke. The statement by P. L. Bellaschi "that multiple strokes of lightning actually may strike the ground at places apart" is probably true only if the ground is without high projecting conducting objects at that point. More interest is involved in whether multiple strokes, once in contact with a relatively high conducting object such as a tree, lightning rod, transmission line, or tall building, is likely to transfer from such an object during the interval of time between successive strokes. The data thus far indicate that such a transfer is unlikely.

The author states also that the "first discharge is apparently the most intense and severe," but the writer does not believe that there is sufficient data as yet to support such a statement. It is the writer's hope that P. L. Bellaschi will disclose the source of his supporting data.

The author's method of measuring current from the appearance of burns on electrodes of deionizing gaps does not seem to lend itself to very satisfactory results from the point of view of accuracy. In figure 8 of the paper, the author shows curve *A*, which has been labeled "direct or near direct strokes of lightning at distribution transformers." Apparently the number of transformers involved multiplied by the number of years equals 4,000. It is also presumed that each transformer was provided with 2 deionizing gaps. It is not stated, but it is further presumed, that the results plotted are to represent the current through a single deionizing gap. However, in order to be able to draw a comparison, as the author has done, stating that "the magnitude of the lightning stroke currents plotted to date, as determined from the various methods discussed, are substantially of the same order," it is necessary that the data be comparable, but this does not seem to be the case. Since the number of lightning discharges is plotted, it is necessary for comparison purposes that the number of installation years be the same, and the data taken on the same basis. Curve *B* of figure 8 of the paper apparently is plotted from table V of the Sporn and Gross paper, "Expulsion Protective Gaps on 132 Kv Lines" (Elec. Engg., v. 54, Jan. 1935, p. 66–73), the data being taken directly without making any correction for the number of installation years. Magnetic link data were taken on 270 towers, and the data are for one year, thus

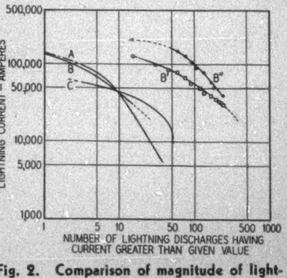

**Fig. 2. Comparison of magnitude of lightning currents as ascertained from 3 different sources**

A, B, and C are the same as the curves in figure 8 of the paper, except that they are plotted in per cent the number of installation years are 270, and a multiplying factor of 14.8 should be used to put the data on the same basis as that reported by P. L. Bellaschi for 4,000 transformer years. The result of this correction is shown in curve *B′* of figure 1 of this discussion. A similar sort of correction should be applied to the data which appears as curve *C* of figure 8 of the paper.

It is very doubtful that comparisons can be made on such a basis anyway, since the fundamental data have been obtained under different conditions and treated differently. As an illustration, Sporn and Gross measured the current in the transmission tower leg, and listed in their tabulation, in the paper just referred to, only the highest tower currents obtained, although several towers may have passed current. Then, based on the traveling wave theory, they arrived at a stroke current which is always larger than the tower current.

Thus, in one case 83,000 amperes in the tower becomes 130,000 amperes in the stroke. P. L. Bellaschi, however, seems to be using the current through a single deionizing gap without making a corresponding correction to arrive at the stroke current. In curve *B* of figure 2 of this discussion the writer has plotted data supplied by W. W. Lewis and C. M. Foust and corrected to 4,000 installations, showing what would be obtained if all of the tower currents believed to be involved in a stroke are added together and assumed to equal the direct stroke current. These data are for the same installations and the same year as that shown in table V of the Sporn and Gross paper referred to previously.

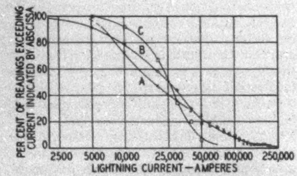

**Fig. 3. Comparison of magnitudes of distribution lightning arrester discharge currents as ascertained from 3 different sources**

A—Curve A of figure 8 of the paper
B—From data of K. B. McEachron and W. A. McMorris
C—Same data as for B, but on assumption that the total current through 2 arresters is twice the current through 1 arrester

All curves are based on the assumption of 4,000 transformer installation years

A much better comparison of these different results may be obtained if they are plotted on a percentage basis as in figure 3 of this discussion. This eliminates the effect of the number of installation years, but removes from consideration the frequency of occurrence. Moreover, it does not make any compensation for the error involved in comparing currents through a protective device on a distribution circuit and the estimated direct stroke current based on measurements of currents through tower legs.

Perhaps a comparison between the results obtained using the magnetic link to measure the current through distribution lightning arresters (see "Discharge Currents in Distribution Arresters," K. B. McEachron and W. A. McMorris, ELEC. ENGG., v. 54, Dec. 1935, p. 1395–99) and those shown by the author as being discharged through deionizing gaps would be of interest. If a correction is made for the number of installations, these can be put on a comparable basis, since they are presumably measuring the same quantity, namely, the current through a lightning protective device associated with a distribution transformer. Such a comparison is shown in figure 4 of this discussion, the magnetic link data having been adjusted to 4,000 transformer years. Since it is not certainly known whether P. L. Bellaschi used the current through 1 or 2 deionizing gaps in determining curve *A* of figure 8 of the paper, the writer plotted also in figure 4 of this discussion another curve in which it is assumed that the total for both arresters would be double that found in one. Using either curve to compare with the curve of the author, it is clear that the comparison is not very good unless the low values obtained by the author and the high values with the magnetic links are discounted. There may be some slight justification for this on the basis that in adjusting the 871 transformer years to 4,000 years it is assumed that the number of readings would be increased by the factor 4.59 which takes no account of the possibility of some higher current than 17,000 amperes occurring during the additional years. There is no doubt that a severe direct stroke of 100,000 amperes or more will occur sometime, which indicates that with data covering a long enough period of time, the frequency of such an occurrence can be obtained. At the present time the data with the magnetic links on distribution gives no evidence of such frequency.

**P. L. Bellaschi:** In reply to the questions K. B. McEachron raises, observations[1] of over 200 discharges indicate the first discharge of a multiple lightning flash is usually much more intense than the succeeding ones in the series. Out of a total of 65 flashes to ground, 50 per cent were single discharges. Values of time interval between successive discharges in multiple lightning[1,2] range from 0.0006 second to 0.53 second.

Records of the 33 multiple lightning flashes show that the successive discharges in each series follow the same path to ground. Other field observations[3,4,5] indicate that successive discharges actually may strike the ground at places apart. More field data will be required before the relative frequency of these 2 behaviors can be established. There is also supporting evidence which indicates that a strong wind movement may shift the ionized path of the lightning channel. As K. B. McEachron suggests, this effect may result in shifting the point of incidence on successive discharges of lightning from the overhead ground wire of a transmission line to the line conductors.

Therefore, with due weight given to the above-stated characteristics of lightning, valuable data on lightning currents are obtained from the field records on the fusion and crushing of conductors. These deductions are stated in the paper.

C. M. Foust states that the use of the magnetic link to measure crest values of surge current is in supplying many field records. In view of the complexity of the lightning stroke discharge, the probable reversal of the currents, and other effects, the magnetic link is susceptible of erratic results. It gives no indication of the duration or nature of the current discharge. For these reasons it is inadvisable to depend solely on this method.

D. D. MacCarthy presents limited data on puncture tests he has made on paper with surge currents from about 1,000 to 10,000 amperes. He gives no information on the method of measuring the size of hole punctured, the kind of paper used or other pertinent data on the test, but from the meager data given he concludes that surge current measurements with the device mentioned in reference 8 of the paper or from a comparison of electrode burning are in error to the abnormal amount he gives. In fact, the proper use of 2 metal disks separated with thin paper of proper quality, in addition to adequate calibration of the hole punctured by means of a densometer, has given more dependable results than D. D. MacCarthy can claim from his limited tests.

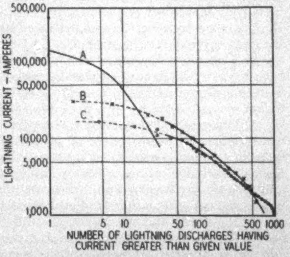

**Fig. 4. Comparison of magnitude of lightning currents as derived from 3 different sources, and showing the result of a different interpretation**

A, B, and C are identical with corresponding curves in figure 8 of the paper
B′ and B″ are plotted from the same data as B, but interpreted differently and corrected to 4,000 transformer installation years

In the paper, however, one of the methods considered in determining lightning currents in the field has been to compare the surface burning produced on the plugs of deionizing gaps with similar effects produced with known currents in the laboratory on corresponding metal surfaces. A comparison of the amount of surface spread and beading enables one to establish the magnitude of current with a degree of accuracy comparable to or not much different from that of the other methods now available.

Curve *A* in figure 8 of the paper gives currents established from the effects produced by the lightning stroke discharge at distribution transformers. Such effects are the surface burning of the electrodes or plugs of deion gaps, other evidences of surface burning to line conductors and discharge paths, shattering of fuse cutouts and other effects or damage. The 4,000 transformer years refer to surge proof transformer installations. Additional data on lightning stroke discharges to these transformers indicate even higher values than in curve *A*.

It is pertinent that since the development of the surge proof distribution transformer, in which case the fuse cutouts are eliminated from the line and the deionizing gaps are designed to discharge currents of lightning stroke intensity, direct strokes at these transformers have been effectively discharged to ground. This ability of the surge proof distribution transformer to handle direct strokes has been substantiated further by laboratory tests with current discharges corresponding to those produced by the more severe lightning strokes.

The 3 curves in figure 8 of the paper have been replotted in figure 5 of this discussion, with the following additions: curve *D* refers to the recent data[6] by W. W. Lewis and C. M. Foust recorded on high voltage lines using magnetic links; curve *E* gives the lightning stroke currents determined by Harald Norinder[2] using a vertical antenna and cathode ray oscillograph measurements of the magnetic induction produced therein by the lightning current discharge. All 5 curves are plotted on the basis of approximately 50 random discharges of lightning currents. They show the relative distribution for various current intensities.

K. B. McEachron has replotted the data of figure 8 of the paper in a number of ways, but it seems to be unnecessary, since the purpose of the curves is to compare separate sets of data on lightning currents for their relative distribution of intensity. Given a substantial number of lightning stroke currents, what is the relative distribution of the current intensity? The answer is indicated in figure 8 of the paper, and even more fully from the 5 curves of figure 5 of this discussion. In all cases the curves refer to current measurements recorded on highly exposed electrical circuits or in the channel of the stroke itself. The plotted values refer to the lightning stroke currents. With more data additional refinements can be made in such comparison.

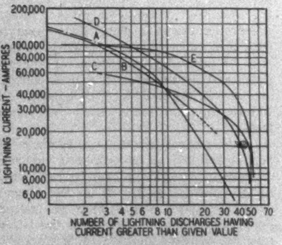

**Fig. 5. Additional comparisons of magnitude of lightning currents**

A, B, and C are identical with corresponding curves of figure 8 of the paper
D—From recent data of W. W. Lewis
E—From cathode ray oscillograph measurements

To answer C. M. Foust's question, curves *A*, *B*, and *C* pass through a common point at approximately 50,000 amperes as a matter of incident. The writer agrees and, in fact, has already stated in previous correspondence[7] that the curves in figure 8 of the paper and figure 5 of this discussion can be appropriately plotted on a per cent basis.

In conclusion, each of the several and different methods now available for investigating lightning stroke currents is valuable since each is capable of giving data supplementing those of the others. The combination of all the methods with due weight to each will enable greater and more rapid progress in the solution of the lightning problem.

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6. Lightning Investigation on Transmission Lines—V, W. W. Lewis and C. M. Foust, Elec. Engg., Sept. 1935, p. 934–42.

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# Economical Loading of Underground Cables

**Discussion and author's closure of a paper by E. A. Church published in the November 1935 issue, pages 1166–72, and presented for oral discussion at the power transmission session of the winter convention, New York, N. Y., January 29, 1936.**

**C. W. Franklin** (New York Edison Company, Inc., New York, N. Y.): There can be no question that the fact of cyclic loading deserves due recognition in the calculation of underground cable ratings, but there may be some question as to the lengths to which refinement of calculation can be carried with profit, for generally the closer the approach to rigorous analysis, the more complicated and tedious these adjustments become. Although an almost exact calculation of cable temperatures can be made for any given set of reference conditions, it is essential to recognize the wide variety of reference conditions which any one feeder encounters in its route, and even more important, the many factors which are not known definitely, simply because it is utterly impracticable to make the numerous measurements. Certain elements of these reference conditions are: the season of the year; location as related to foreign heat sources; composition and moisture content of surrounding earth; size and configuration of duct bank; inner or outer position of duct in bank; nonuniformity of thermal resistivity and dielectric loss; size and loading characteristics of cables in common duct bank.

The author has pointed out in the latter part of his paper that for various standard sizes of cable certain duct bank sizes give minimum overall investment per unit of capacity when arbitrary thermal limits are set up. The writer too has made similar computations and has arrived at approximately the same evaluations. There is, however, another important factor involved in the complete economic picture of the problem, and that is the optimum level of maintenance. Investment furnishes only the index to the fixed charges.

This factor of maintenance cost is a phase of the unanswered question of the relation between cable failure rate and operating temperature. Could not cable loading and, consequently, temperature be increased appreciably above present A.I.E.E. standards even at a possible expense of accelerated failure rate, with a resultant decrease in overall unit cost? In view of the long life of cable and duct, and the preponderance of fixed charges over maintenance expenses and cost of losses, there is an excellent prospect that "putting" the investment to work a little more strenuously and accepting, if necessary, a somewhat shorter cable life will prove distinctly economical. It should be remembered, however, that the permissible increase in failure rate is limited by practical design considerations for a given system, and that limitation is dictated by that rate which necessitates further reserve in other feeders and equipment.

F. M. Clark's paper, "Pyrochemical Behavior of Cellulose Insulation" (see Elec. Engg., v. 54, Oct. 1935, p. 1088–94) appears to be an important contribution to the great fund of information which will be required eventually to answer the question of cable performance at higher copper temperatures. Within the past two years, the company with which the writer is connected has pursued the problem by means of tests on completed cable. With continuous excitation at normal voltage daily load cycles were applied, first in the laboratory and later in the field, to limited amounts of 15 kv paper insulated cable of one particular size and type. The laboratory tests indicated 100 degrees centigrade as the approximate upper limit of copper temperature which could be endured by these samples without visible evidence of deterioration of the paper tapes. The field tests, therefore, are being made with a load current which produces about that temperature. No further statement concerning results will be made at this time inasmuch as the field tests still are in progress.

With reference to the conclusions of the author regarding the economical size of duct bank, it might be added that new duct banks constructed with inner ducts are to be avoided, except perhaps in specific locations where construction to a width of 2 ducts would be markedly more expensive.

Often it happens that the route of a particular feeder encounters but a few sections of duct where, because of unusually large and heavily loaded duct banks or because of external heating, the duct temperatures are, say, 5 or 10 degrees higher than those of the 100 or more remaining sections. Economy dictates that the feeder should be rated without regard for these few hot sections, for otherwise almost the whole investment in the feeder would be forced to a lower level of utilization by the insignificant investment in a few sections. If the added risk of failure in these few sections could not be tolerated, the cost of replacement with cable of greater cross section could well be afforded.

**G. B. Shanklin** (General Electric Co., Schenectady, N. Y.): E. A. Church's paper is one of the most valuable contributions to the subject of underground cable loading of recent years. It practically completes the work on loading of cables in ducts, initiated by an Edison Electric Institute committee some years ago. The committee work was empirical and based on actual field surveys throughout the country under typical central station load conditions. The author expresses these empirical results in mathematical form, and there is close agreement between his theoretical method and the committee's actual field surveys.

The committee's work resulted in standard loading tables for typical daily loads of from 50 per cent to 100 per cent load factor. Within this range the author's theoretical method is not needed. Its real value is that it will allow us to determine loadings under special conditions not covered by the standard tables; namely, for very low load factors and for emergency overloads.

In general, the author's conclusions are verified by this previous work. The writer participated in this, and any differences of opinion he may hold are not based upon the mechanics of procedure but upon interpretations of some of the safe limiting factors.

The writer fully agrees with E. A. Church's contention that it is not economical and not even good engineering to group closely a large number of loaded cables. His recommendation to limit the group to 12 cables or less is sound.

His conclusion that excessive duct temperatures are likely to bake out the surrounding soil and cause trouble is sound also, but his limit of 50 degrees centigrade idle duct temperature seems a little low, except possibly for very porous soils such as pure sand. I would rather set the limit as 50 degrees centigrade for the outer surface of the conduit structure in actual contact with the soil. On this basis, tables V and VI of the paper seem to agree more closely. In this connection, care must be exercised in applying American temperature limits to cable buried directly in the earth. European engineers learned years ago about the dangers of baking out soil, and reduced temperature limits for buried cable accordingly.

The author seems to feel that existing A.I.E.E. temperature limits for solid type impregnated paper cable are conservative. In this the writer cannot agree. They are from 5 to 10 degrees above safe limits, and not only do present limits result in rather high soil temperatures, as pointed out by the author, but also they result in an excessive burden on the lead sheath of thoroughly impregnated modern cable. Operating records show this rather clearly, for there are many lead sheath splits and many duct-mouth and expansion-bend sheath failures developing. Better lead sheath will not entirely cure this type of trouble.

Another characteristic of American loading practice, that of giving increased winter load ratings up to the maximum allowable copper temperature, requires careful consideration. For 100 per cent daily load factors this practice is not objectionable but for smaller load factors it causes a correspondingly greater fluctuation of daily temperature, thus placing a greater burden on the lead sheath and aggravating void formation and ionization deterioration. Either the present A.I.E.E. temperature limits should be decreased or maximum loading should be determined on the basis of maximum allowable temperature range, rather than on maximum temperature.

The author describes 2 methods of taking care of emergency overloads. One is conservative and the other is liberal. The conservative method never allows the emergency overload temperature to exceed standard A.I.E.E. temperature limits while the liberal method allows such an excess. The writer is glad to see that the author follows the customary, or conservative, method. All classes of insulated electrical apparatus are involved in the principles at issue, and the writer would not like to see a national body such as the A.I.E.E. adopt the so-called liberal method, because eventually the limits would become more liberal and manufacturer and operator would suffer alike.

No operator can be criticized for disregarding temperature limiting rules in an emergency that absolutely demands it, but the changing of well-established rules to meet such emergencies is a very different matter.

**Herman Halperin** (Commonwealth Edison Co., Chicago, Ill.): The author is to be congratulated on having developed an acceptable and mathematically exact method of determining the ratings of cables under cyclic loading. The calculations required, however, are laborious. It seems that ratings under cyclic loading may be determined with equal accuracy by simpler methods.

The thermal characteristics of the conduit and surrounding soil are exceedingly variable. The type of soil, the amount of moisture it contains, the number of ducts and cables in the conduit, and the conduit's depth below the surface largely control the thermal resistance of the duct structure. All these factors usually vary widely along the route of any underground line. The condition of the soil likewise varies widely with the seasons. In order to determine accurately the maximum capacity of a line, it is first necessary to know the thermal characteristics of that part of the conduit along the route of the line where the characteristics are the poorest. The thermal characteristics of the conduit may vary as much as 50 per cent to 100 per cent at a given location during a year, with no change in cables. The necessary information on thermal conditions in conduits can be obtained only by continual field surveys of duct temperatures. The nature of the data as found in Chicago does not justify the exact computations proposed by the author.

In the company with which the writer is connected a group of 4 men make continual surveys of thermal conditions in the underground system and do allied work in the office. It has been found from many years of experience that the duct temperature over a period of 24 hours usually does not vary more than 1 or 2 degrees centigrade, even though the load varies from hour to hour. The duct temperature can be calculated easily from the average 24-hour power loss of the cables in the conduit, together with the data on the thermal resistance of the conduit obtained from temperature surveys. The accuracy is as high as may be obtained feasibly by any method.

Another accurate approximation is used in calculating the rise of the temperature of the cable above that of the duct. For Chicago conditions, it has been found that the maximum copper temperature can be calculated by assuming that the average value of the load over the 3 hour period when the daily load is highest gives the same temperature rise as the actual cyclic load. The accuracy is about the same as the accuracy obtained by the use of exact methods. The method was developed from analysis of typical load curves.

The foregoing indicates the methods by which line ratings, maximum copper temperatures, and duct temperatures can be predicted with dependable accuracy for lines under cyclic loading in the underground system of the company with which the writer is associated. The method is much simpler than E. A. Church's harmonic analysis and the amount of field data required for best results is the same in both cases. By maintaining an accurate and continuous check on cable temperatures in Chicago, the maximum use of the investment in underground lines is obtained.

It has been recognized for some time in Chicago that it is not the continuous rating but the emergency rating that usually determines when an additional line must be installed. Emergency ratings were used 10 years ago on special lines as they were needed. Emergency ratings are in use for all 66-kv and 132-kv lines and on a few 4-kv and 12-kv lines. Aging tests are being conducted now on 3-conductor 12-kv cables with a view to making extensive use of emergency ratings on all 12-kv cables and using, on rare occasions, temperatures higher than the A.I.E.E. limits for short portions of lines in relatively warm conduits. In this way, advantage will be taken of the fact that 12-kv lines have been so improved that the rate of failures in Chicago is only $^1/_5$ of the rate of about 12 years ago.

The method used in determining emergency ratings is the same as that described in this paper. The calculations are somewhat different, being based on the form of solution of the fundamental heat flow equations as given in a previous paper (see "Thermal Transients and Oil Demands in Cables," K. W. Miller and F. O. Wollaston, A.I.E.E. TRANS., v. 52, Mar. 1933, p. 98–110).

The statement that cumulative heating tends to occur in conduits heated beyond a critical temperature of 50 degrees centigrade is in close agreement with operating experience in Chicago. The statement that cable ratings are frequently limited by the maximum temperature of the duct rather than of the cable, particularly for larger cables, for high load factors, and for summer conditions when the base temperature is high also is in accord with our findings.

The writer cannot agree with the statement at the end of the paper that "the winter load generally is so much higher than the summer load that it may be used as the limiting factor in determining the ratings."

The rating does not depend on the load in any way, although it is affected by the shape of the load curve. Summer conditions are the limiting factors for Chicago.

In another previous paper on cable economics for Chicago conditions (see "Economics of High-Voltage Cable," D. W. Roper, A.I.E.E. TRANS., v. 50, Dec. 1931, p. 1399–1410), the findings were in agreement with those of the present paper except in one important particular. Figure 5 of E. A. Church's paper shows that the annual charges per kilovolt-ampere per mile for 500,000 circular mil 15-kv cables and larger, and for 400,000 circular mil 25-kv cables, increase quite rapidly as the number of cables in the conduit increases above 4. In the writer's study referred to, it was found that the annual charges for cables of comparable sizes and operating voltages tended to remain about the same or to decrease slightly as the number of cables in the conduit increased from 3 to 10. Practical experience in Chicago indicates that the cost per foot of duct is substantially lower for a 12-duct conduit than, for instance, for a 6-duct conduit. The cable ratings do not continue to decrease indefinitely as the conduit size increases, unless the total heat losses become great enough to dry out the surrounding earth. Regardless of the number of ducts in the conduit, each cable is affected thermally by only the the few cables immediately adjacent to it. There is also greater diversity of load in a large group of cables, and the maximum total coincident heat loss averages less per cable than in smaller conduits. These factors tend toward greater economy in moderate size and large conduits. Another point is that frequently in Chicago the cooling effect of moisture in the soil, or water in soil and conduits appears when large conduits are built.

**A. H. Kidder** (Philadelphia Electric Co., Philadelphia, Pa.): Advance toward a well-rounded practical solution of the problem of underground cable loading apparently requires much the same method of approach that E. A. Church has taken. The writer is considerably encouraged, however, by the thought that a time of diminishing practical need for the use of the powerful but rather cumbersome methods of harmonic analysis is approaching. For instance, the author's work appears to demonstrate that the copper temperature rise above duct wall may be quite accurately represented by a simple exponential heating curve. If this is the case, there is little further need for harmonic analysis in calculations of copper temperature rise above duct wall.

The writer's principal interest, therefore, has been in the behavior of the duct wall temperature during load transients. It is believed that the methods of harmonic analysis at present hold the key to an understanding of this phase of the problem. For this reason the writer reviewed E. A. Church's work quite carefully. In the course of the review a few points which may be helpful to others were found.

Cyclic temperature impulses evidently travel very slowly through earth, and attenuate very rapidly. This may be illustrated quite simply. Equation 10 of the paper needs very little modification to obtain an expression for the temperature $T_r$ induced at radial distance $r$, between the limits $r_d$ and $R_2$, in terms of the heat input $Q_d$ at the inside radius $r_d$ of the sending duct,

$$T_r = \frac{S_e}{2\pi q_e r_d \tau_d} Q_d \sigma_r \qquad (1)$$

in which $\sigma_r$ is a function of $q_e r$ and $q_e R_2$, while $\tau_d$ is a function of $q_e r_d$ and $q_e R_2$. From this, the ratio of the induced to the sending temperatures is found to be $\sigma_r/\sigma_d$ for any frequency of oscillation. When $R_2$ is large, in a medium having the constants given in table III of the paper, this ratio reduces from about 50 per cent for the steady state at a radius of one foot, to less than 4 per cent for the fundamental and the higher harmonics of the daily copper loss curve. The angle of lag is very nearly $q_e/\sqrt{2}$ radians per foot of radial distance between $r_d$ and $r$. The wave length is, then, about $2\pi\sqrt{2}/q_e$ feet, and the velocity of temperature propagation becomes approximately $\sqrt{2\omega/C\rho S}$ or about one inch per hour for the fundamental harmonic in this medium.

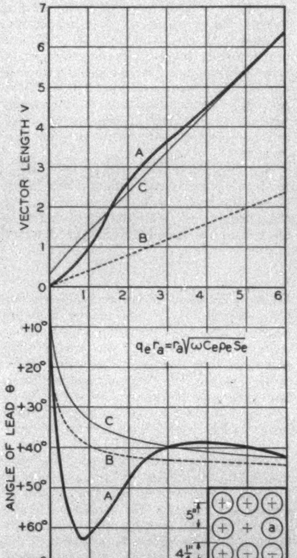


**Fig. 1. Earth admittance function for 8 ducts plotted in the dimensionless form**

$$\frac{S_e Q_2}{2\pi T_a} = V\angle\theta$$

A—Hottest of equally loaded ducts shown in the inserted cross section
B—Plot of equation 10 of E. A. Church's paper.
C—One loaded duct only

These effects apparently have been overlooked by the author in his use of equation 10 of the paper for calculating the earth impedance data summarized in table III just referred to. Fortunately, however, very little additional analysis is needed to develop a fairly comprehensive earth impedance function for any number and arrangement of equally loaded cables in any medium.

Assume that ducts $a, b, c, \ldots, n$ lie within a given duct run. The temperature rise of any given duct is the rise due to its own heat input, plus an additional rise induced upon it by the heat input at each of the other ducts. If the duct sizes are identical, the approximate average temperature rise over the inside surface of duct $a$ may be written directly from equation 1 of this discussion in terms of the various heat inputs $Q_a, Q_b, Q_c, \ldots Q_n$ at radial distances $r_a, r_{ba}, r_{ca}, \ldots r_{na}$ from the center of duct $a$:

$$T_a = \frac{S_e}{2\pi q_e r_a \tau_a} [Q_a \tau_a + Q_b \sigma_{ba} + \ldots + Q_n \sigma_{na}] \qquad (2)$$

This equation holds for each harmonic, regardless of the respective amplitudes or time phase displacements between $Q_a$ and the other heat inputs. If it is assumed, however, that $Q_a = Q_b = \ldots = Q_n = Q_2$, this equation may be reduced to an impedance function of the following simplified nondimensional form:

$$\frac{2\pi T_a}{Q_2 S_e} = \frac{\sigma_a + \sigma_{ba} + \ldots + \sigma_{na}}{q_e r_s \tau_a} \qquad (3)$$

At this point it is interesting to observe that the substitution of $q = 0$ in the $\sigma$ and $\tau$ terms of equation 3 of this discussion gives the familiar steady thermal impedance characteristic

$$\frac{2\pi T_a}{S_e Q_2} = \ln\left[\frac{R_{2N}}{r_a r_{ba} r_{ca} \ldots r_{na}}\right] = N \ln\frac{R_2}{R_1} \qquad (3a)$$

if $R_1$ is taken as the $N$th root of the product of the $N$ radii $r_a, r_{ba}$, etc., and $R_2$ is the outside radius of the equivalent cylindrical duct structure.

Since the value of equation 3 of this discussion at $q = 0$ may be found readily from equation 3a, an excellent graphic representation of this function usually may be obtained without need for calculations at other values of $q_e r_a$ less than 0.20. When $q_e r_a$ is greater than 0.20 and $R_2/R_1$ is greater than 5, $R_2$ loses all practical significance in the $\sigma$ and $\tau$ terms of equation 3 of this discussion, and the following simpler expression is then adequate for practical calculations:

$$\frac{2\pi T_a}{S_e Q_2} = -\left[\frac{K_0 q_e r_a\sqrt{j} + K_0 q_e r_{ba}\sqrt{j} + \ldots + K_0 q_e r_{na}\sqrt{j}}{q_e r_a\sqrt{j}\, K'_0 q_e r_a\sqrt{j}}\right] \qquad (3b)$$

Equation 3 of this discussion then may be plotted quite readily for any cable configuration by the aid of H. B. Dwight's tables ("Bessel Functions for A-C Problems," A.I.E.E. TRANS., v. 48, July 1929, p. 812–20) of these functions:

$$K_0 x\sqrt{j} = \text{ker } x + j \text{ kei } x \text{ and}$$

$$\sqrt{j}\, K_0' x\sqrt{j} = \text{ker}' x + j \text{ kei}' x$$

The accompanying figure gives reciprocals of the impedance values calculated from equation 3 of this discussion for one of the hottest of 8 equally loaded cables in the outside ducts of a 9-cable 4-inch terra cotta duct run. The vector length, plotted in this form for the case of a single cable is practically a linear function of $q_e r_a$. The deviation from the linear characteristic for more than one cable is due entirely to the attenuation and time phase displacement of temperatures induced by the other cables on cable $a$. With fewer cables this effect is less. It is interesting, however, to see how rapidly the vector length approaches the single cable normal, even within the usual working values of $q_e r_a$ which lie between 0.5 and 1.5 for the first 4 harmonics of the daily copper loss curve. Beyond 0.5 the admittance is probably 2 to 3 times as high, or the impedance less than $^1/_2$ as great, as would be calculated from equation 10 of the paper for the same number and arrangement of cables, regardless of the actual values assigned to $C$, $\rho$ and $S$.

A point of special interest to the writer at present is that the fundamental and higher harmonics transmitted between ducts in the same run probably have much less effect upon the temperature of the hottest duct wall than E. A. Church has estimated in this work. To summarize briefly, it appears that the number of cables in the duct run has very much less effect upon emergency load temperatures than upon normal load temperatures. If subsequent analysis shows the cyclic earth impedance to be of minor consequence in emergency load impulse calculations, so much the better. If this is not the case, however, it may be found that the duct wall temperature rise also can be approximated for a rectangular impulse in a representative configuration up to, say, 10 hours' duration, by the use of an exponential equation with a relatively high time constant.

Harmonic analysis is giving us for the first time a method for determining to what degree the thermal impedance of the duct run may be improved under all normal and emergency load conditions by possible control of the now rather capricious thermal constants $C_e$, $\rho_e$ and $S_e$. The writer frankly hesitates to assume that engineers will be satisfied to accept without question the pay load limitations now imposed upon underground cables by wide variations in these thermal constants and by the present high thermal impedance of the air pocket between cable sheath and duct wall. Under normal daily load cycles these 2 factors appear to be responsible for about $^2/_3$ of the copper temperature rise above ambient. For emergency load impulses the air pocket alone is probably responsible for about $^1/_2$ of the emergency copper rise.

There appears to be considerable opportunity for improvement and it is believed that the tool which the author has provided may have a very practical effect upon progress toward a solution of this important problem.

**E. A. Church:** G. B. Shanklin's proposal to rate cables on the basis of maximum temperature variation is very interesting. In the writer's opinion, however, this should not be the only criterion for safe limits any more than should maximum copper temperature limit. The maximum temperature variations permissible can be learned only by experience, with maintenance costs taken into account.

Experience on different systems will also dictate the maximum allowable duct temperature for various soils. The writer's experience has been that 50 degrees centigrade is a safe limit, and this is verified by Herman Halperin for Chicago conditions.

On this basis there are three limits on which to base cable ratings; maximum copper temperature, maximum sheath and copper temperature variations, and maximum average duct temperatures. It should not be necessary, therefore, to change the A.I.E.E. rule for maximum copper temperature, which is probably about right for continuous load.

It is interesting to observe that some trouble has been encountered in Boston with sheath cracking on cables which are carrying heavy loads with extreme variations. Most of them, however, are in small manholes with inadequate racking facilities. On most of these cables, steps have been taken to smooth out the load variations by changes in operating schedules, with a resultant greater economy in cable loading. Experiments are being made with flexible joints in some of these small manholes in order to reduce the flexing of the lead under load cycles.

Halperin has made a good case for periodic temperature checks on conduit lines and is basing cable loadings on the results of these tests. Such an extensive program has not been considered economically justified in Boston, and reliance is placed more on theoretical calculations and periodic temperature checks on lines known to be loaded continuously near their maximum theoretical ratings. In the past the tests have indicated that the ratings on these lines are about right.

Halperin states also that for Chicago conditions the annual charges for transmission decrease as the number of ducts in a conduit is increased from 3 to 10. It seems that each company should make its own economic study of cable loading, using cable ratings and costs peculiar to its own conditions. Difficult digging might easily raise the cost of 12-duct conduits in relation to 4-duct conduits. The suggestion of C. W. Franklin to include maintenance costs at different loadings in any such economic study is pertinent in this regard.

A. H. Kidder states that the paper seems to demonstrate that copper temperature rise above duct wall may be quite accurately represented by a simple exponential curve. If he refers to figure 3 of the paper, this is not quite true, since these curves were computed from equations 11 and 12 of the paper and are based on Bessel functions. The cylindrical configuration is responsible for this fact. The temperature in a cable rises faster at first, then more slowly than the simple exponential function. With proper choice of exponents, exponential curves may be made to fit the time-temperature rise curves at three points: $t = 0$, $t = \infty$, and at some intermediate point giving an approximate solution. A somewhat different approach to the problem of copper temperature rise above duct air may be found in a previous paper ("Thermal Transients and Oil Demands on Cables," K. W. Miller and F. O. Wollaston, A.I.E.E. TRANS., v. 52, Mar. 1933, p. 98–110).

The point which A. H. Kidder makes in regard to the extremely slow speed at which the temperature cycles proceed through the earth and conduit structure is well made, and it must be admitted that this point was overlooked in the calculations made in the paper, where it was assumed that the equivalent inner radius $R_1$, which is correct for the steady state, is correct also for the transient condition. A. H. Kidder has made a distinct contribution by developing the more accurate expression given by equation 3 of his discussion. The error increases as the number of ducts in a conduit increases. On this basis, the ratings for cyclic loading given in table V of the paper are conservative, and computations made from Kidder's equation 3 produce values from 2 per cent to 4 per cent higher, depending upon the load cycle and number of ducts.

## Breakdown Curve for Solid Insulation

**Discussion and author's closure of a paper by V. M. Montsinger published in the December 1935 issue, pages 1300–01, and presented for oral discussion at the electrical machinery session of the winter convention, New York, N. Y., January 29, 1936.**

**P. L. Bellaschi** and **W. L. Teague** (Westinghouse Elec. and Mfg. Co., Sharon, Pa.): In insulation studies the 2 important factors are the voltage and time of application. In this respect the author gives interesting data which apply, however, for the specific case of $^1/_{16}$ inch pressboard tested between a square edged electrode and a plate. Similar tests have been made by the writers. It is of interest to compare the 2 sets of data.

Investigations have been made of the strength of 0.056-inch oil-treated pressboard between a $2^1/_2$-inch square-edged disk and a 6 inch plate, as indicated in figure 1 of this discussion. The tests were made in oil at temperatures of from 15 to 25 degrees centigrade. Sixty-cycle voltages were applied for one minute, for a few seconds, and for a few cycles. In addition, tests were made which consisted of switching and impulse voltages of positive polarity, the switching surges rising from zero to crest voltage in about 700 microseconds and the impulse voltage having practically a $1^1/_2$ x 40 microsecond wave.

Since the strength of pressboard may vary with the specific material, treatment, etc., the volt-time curve of breakdown in figure 1 for 0.056-inch oil-treated pressboard and Montsinger's curve for 0.0625 inch material show close similarity and agreement. However, all observations and data on the test need be considered in order to set forth the full significance of its volt-time curve of breakdown.

First, it should be noted that tests indicated at 700 microseconds permit drawing a full line over the relatively wide range of time between the impulse and 60-cycle voltages, which Montsinger naturally has shown in his paper as a dotted line. Furthermore, observations on the corona and the nature of breakdown indicate pertinent characteristics. Unless these factors are given proper consideration the conclusions derived from the volt-time curve of breakdown alone may prove misleading. It was found that impulse and switching corona became visible at 60 kv. At the breakdown impulse voltage the corona streamers extended radially 2 inches and more from the electrode edge along the pressboard surface. For the limited tests made on each specimen no damage was apparent on the surface of the pressboard due to corona streamers.

Quite a few sample barriers were tested. In the impulse tests breakdown occurred invariably at or near the crest of the wave or on the rising front upon a further increase in voltage. Ten per cent of the failures occurred at the edge of the disk. About 65 per cent were at distributed points, between $^1/_4$ inch and $^3/_4$ inch from the edge, and the remaining 25 per cent near the center. Even when failure occurred on the rising front many were inside the edge. The distribution of these failures is quite uniform over the area of the electrode, indicating on the strength of this evidence that the impulse breakdown is independent of the edge effect. The streamers along the pressboard (in the oil) may account for some shielding of the edge. The switching surges gave even more diffuse streamer formation than the impulse. In this case 2 of the failures were inside the edge, one at the edge, and the fourth occurred as a creepage over the pressboard sheet, puncturing the insulation at a point opposite the edge of the 6 inch ground plate. All 60 cycle tests indicated failure at the edge. The 60 cycle audible corona is also drawn on the curve, visible corona appearing at a somewhat higher voltage.

Tests by the writers on $^1/_8$ inch solid insulation show that the volt-time curve of breakdown is of a similar shape to figure 1, the voltage values naturally being higher.

From figure 1 the impulse ratio of the pressboard tested is close to 3. The impulse and switching corona level is only 50 per cent of the breakdown value. It is apparent that the insulation of the test specimen is not representative of the insulation designs found in practice.

The data presented by F. J. Vogel, Montsinger, and the writers may not permit building up elegant theories of insulation breakdown but undoubtedly these data give the experimental basis without which no sound theory can be constructed. The 3 subdivisions to which Montsinger refers have been recognized in part in the past, though they now appear to be better identified. Even then such subdivisions may serve more the purpose of convenience in classification. It is generally recognized that dielectric losses, heating, etc., characterize insulation stressed at industrial frequency and voltages. Impulse and switching voltages appear to subject the insulation to a truly dielectric or disruptive effect. This disruptive breakdown requires a certain minimum time to be produced so that at the very short time impulses, in the order of a microsecond, the impulse voltage for breakdown must increase.

For transformer oil the volt-time breakdown curve is given by figure 2 of this discussion. The temperature of the oil in these tests was from 15 to 20 degrees centigrade. As in the pressboard tests, the oil was of good quality such as is supplied with transformers. The gradual downward trend of the volt-time curve for the oil in figure 2 differs in comparison to the curve for solid material, figure 1. In these tests on a $^1/_4$ inch oil gap, corona and breakdown apparently occurred simultaneously. It may be noted that at the impulse voltages the curve rises rapidly with decrease in time application. Oil is characterized by long time lag; on lowering the impulse voltage, breakdown appears on the tail of the wave. The impulse ratio for the $^1/_4$ inch oil gap is almost 2.0.

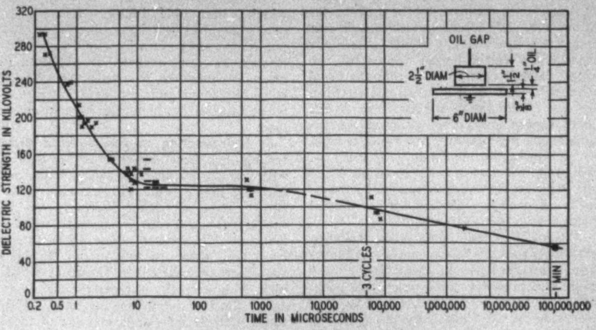


**Fig. 2. Volt-time breakdown curve for transformer oil**

Short lines indicate hold values, $1^1/_2 \times 40$ microsecond wave
Crosses indicate breakdown values

Insulation structures encountered in apparatus are combinations of solid and liquid insulation and have impulse and 60 cycle characteristics which are described in full in 2 papers. (Reference 2 of the paper and "Factors Influencing the Insulation Co-ordination of Transformers, II," P. L. Bellaschi and F. J. Vogel, ELEC. ENGG., June 1934, p. 870–6.) For example, the impulse ratio of transformer major insulation is close to 2.2. The insulation and electrode arrangement and therefore the impulse ratio and corona level for the relatively thin sheet of pressboard between sharp edged electrodes differ substantially from those in well designed apparatus. Consequently the test data given in figure 1 are limited in scope and relative importance. It would be erroneous to apply these data directly to the general problem of apparatus insulation co-ordination. However, one important characteristic is shown by figures 1 and 2, i. e., practically constant impulse ratio in the insulation strength maintains from about a microsecond to a few cycles. This characteristic undoubtedly applies to transformer insulation in general. Its importance is apparent.

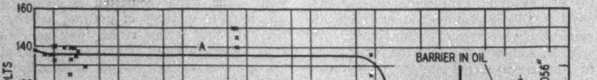


**Fig. 1. Curves obtained in tests on oil treated pressboard**

Curve A—Dielectric strength
Curve B—Visual corona voltage
Curve C—Audible corona voltage

**I. W. Gross** (American Gas and Electric Co., New York, N. Y.): Although the principles of insulation co-ordination on a power transmission system were outlined in a paper before this Institute some 8 years ago, progress in reducing these principles to a practical working basis has been comparatively slow. While considerable thought and study have been given to this problem, it was soon found that one of the greatest hindrances was the lack of fundamental data, such as the magnitude and shape of lightning voltages, the magnitude and effect of switching surges, and the breakdown characteristics of insulation under impulse conditions. Another indefinite factor was the protective characteristics of the lightning arrester as actually installed in service.

During the past few years much progress has been made in developing instruments for measuring and in the actual measuring of some of these fundamental characteristics. The present paper is a distinct contribution in that it gives a fundamental picture and data on the impulse characteristics of insulation such as enters into many types of apparatus on a basis that lends itself to coordination with other parts of the system insulation.

One of the first attempts to co-ordinate transformer insulation with the rest of the system was the use of the suspension insulator as a yardstick. This measuring stick had 2 weak points: first, it required too large steps in going from one insulator step to another (for example, from 3 to 4 is a 33$^{1}/_{3}$ per cent step) and second, the unit of measurement—the insulator—did not have the same electrical characteristics with respect to time and polarity as the built-up insulation of the transformer.

The next step was an attempt to coordinate the tranformer on the basis of a rod gap. Here the nonuniform characteristic of the insulator measuring stick was eliminated, but the scheme still had the defect of using as a measuring stick a device which had characteristics quite different from those of the transformer insulation.

Until recently it has been asserted that the impulse strength of a built-up insulation, such as transformer windings, is a flat straight line irrespective of time; that is, there is no upturn of the curve in the range from zero to 2 microseconds. More recently, however, the fact that even this built-up insulation does have a time lag similar to, although very much less than, that of a rod gap, has been appreciated, and some attempt has been made to use this information to advantage in the coordination of transformer insulation.

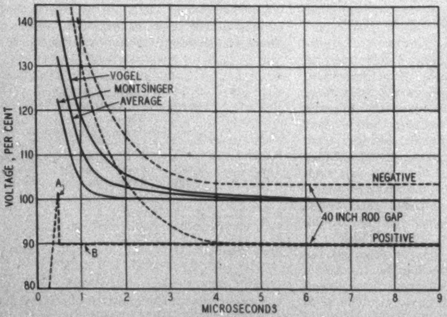


**Fig. 3. Curves showing characteristic impulse strength of fibrous material, typical of transformers**

A—Lightning arrester initiation voltage (100 kv per micro-second)
B—Lightning arrester protective level (1,500 ampere discharge)

In figure 3 of this discussion the 3 solid line curves represent the general trend of the impulse strength of built-up insulation which is typical of transformer insulation, the data being obtained from the present paper and Vogel's paper in 1933. In this figure is also shown the characteristic curve of a 4 inch rod gap set on a long time positive polarity basis approximately 10 per cent below the so-called transformer curve.

It is not intended to imply, however, that a 10 per cent margin for a protective device is sufficient leeway. Here the rod gap supplied no protection up to approximately 2 microseconds on positive impulses and none at anytime for negative impulses. The characteristics of a modern lightning arrester (data obtained from present catalog figures) are shown as the lower curve in figure 3. Here again, the lightning arrester protective level has been arbitrarily set 10 per cent below the transformer, and it will be seen that the overshoot of voltage when the arrester first comes into action is well under the insulation curve of the transformer, although it would be above it if the transformer insulation characteristic were a straight line.

Assuming that Montsinger's and Vogel's data, although taken on samples of specially prepared insulation, actually indicate the characteristics of a transformer, we still see it is necessary to consider carefully the characteristics of the arrester in combination with the transformer strength if protection against steep front lightning surges is to be obtained.

Some older types of arresters have a higher ratio of initial breakdown to sustained voltage than present types, and here it is more important to analyze the relation between the arrester breakdown value and the short-time impulse strength of the transformer.

Another field of insulation strength covered by Montsinger is in the range of switching surges. Here again fundamental data are very scarce, and most conclusions are based on the fact that few insulation failures are reported as a result of switching surges. While experience is not to be ignored, we should keep in mind that we still lack fundamental data on both magnitude and frequency of these switching surges and the breakdown characteristics of insulation when subject to such surges. This consideration of switching surges must be kept in mind in setting up any plan of insulation levels in a workable insulation co-ordination scheme.

It is hoped that data of the type presented by Montsinger will be forthcoming in ever increasing volume, and that they may be eventually extended to complete pieces of apparatus as well as on the separate parts of the insulation which enter into insulation construction.

Now that there seems to be good evidence of the additional insulation strength of wound insulation in the short time range, and since it seems certain that advantage of this will be taken in establishing insulation levels and applying lightning arrester protection, it seems important to consider the advisability and possibility of setting up some type of commercial test on transformers to determine that the impulse strength in the short time range is actually there in practical transformers.

**C. F. Hill** (Westinghouse Elec. and Mfg. Co., E. Pittsburgh, Pa.): This paper on the variation of breakdown of oil soaked pressboard with time of voltage application is interesting, but I do not believe the *B* region can be accepted as real without further data on some physical explanation of why it exists. Breakdown tests require a large amount of data before conclusions can be drawn, due to the spread of the values obtained. No doubt there is a *B* region, which is a transition from the purely electrical type of breakdown (which includes the *A* region of the paper) to the region which involves the electrothermal type of failure (the *C* region). However, the transition from one to the other certainly is gradual and not discontinuous as his curve indicates. I am inclined to conclude that the distortion due to the logarithmic scale plus the normal spread of his breakdown data has led to the flatness of the *B* region.

It would be of value to the insulation engineer to know how long the pressboard was soaked in oil before the tests. Breakdown tests on oil-filled materials of this kind vary widely with time of soaking because of the trapped air in the paper, this air being gradually absorbed by the oil.

The author seems to believe the edge effect of the electrodes was absent for $^{1}/_{4}$ cycle to 18 cycles. As this includes only about 9 actual breakdown values, there are hardly enough data to draw such a conclusion.

Other information of value to the reader would include the time when the various data were obtained, the chronological distribution to insure constancy of material.

Combining the data of the author and those presented by P. L. Bellaschi in his discussion gives some clues which may furnish a physical explanation for part of Montsinger's curve, that is, the *A* region. The *C* region is, of course, explainable in that it constitutes the range in which heat-electrical breakdown occurs. The *A* region may be explained in that this part of the curve is the characteristic of oil and that for an oil-cellulose combination, as in oil soaked pressboard, where the oil has specific inductive capacity value of 2.2, while cellulose has a value from 6 to 8, most of the stress just after voltage is applied is exerted on the oil. This causes the oil to ionize strongly, building up to an avalanche which leads to complete puncture. The *B* region of Montsinger's curve and the same region of Bellaschi's data seem to agree well enough. It might even be suspected that the curves dip in the region of 100 microseconds, giving a multivalued curve. I believe this is very unexpected in a solid dielectric, and a physical mechanism from 2 dissimilar dielectrics in series seems improbable.

The *A* and *B* regions in comparison with the *C* region are, of course, very much magnified by the logarithmic scale used. The *A* region seems explainable but the flat characteristic of the *B* region is unexpected even with the combination of oil and pressboard. Unfortunately the data are too few in the *B* region to show the trend of the curve.

It might be well to call attention to the fact that continuous potentials are used in the *A* and *B* regions, and alternating potentials are used in the *C* region. A better method of approach from the fundamental point of view would be to use direct current over the whole range and determine breakdown as a function of rate of voltage rise. It would be of interest if both investigators could perform this same experiment on a true solid insulation.

**J. B. Whitehead** (The Johns Hopkins University, Baltimore, Md.): The experimental results presented in this paper do not represent the inherent breakdown characteristics of the materials tested. They are definitely related to the configuration of the electrodes and to the medium in which they are immersed.

A descending type of curve for long-time breakdown values is in accordance with the results of many other workers. However, the values obtained here are probably influenced by the sharp edge of the upper electrode and consequently it is by no means proved that the curve as given is typical of the material. Moreover, the law of the inverse fourth root of the time has been frequently questioned by other workers and a wider range of time is necessary before this law can be said to be established.

The suggestion of a correlation between the proposed 3 systems of breakdown and those suggested by Moon and Norcross would seem to be unfortunate. The curves of the latter authors involve temperature as a variable. Similarity of the forms of the curves in the 2 cases would indicate the third region as between *B* and *C* rather than at *A*.

I question whether there are really 3 distinct regions or types of breakdown. It is my opinion that under controlled conditions limiting the breakdown to the properties of the material itself the *A* region would be eliminated and the *B* region continued horizontally to zero time.

The ascending values of the *A* region seem to me to be inherent in the joint capacitance and conductance values of the electrode arrangement rather than as explained by the author. In this region an initial surface ionization and corona evidently forms around the smaller electrode dependent upon the surface and interface properties of the sheeet insulation and the oil, resulting in an increased value of capacitance. The charging of this capacitance reduces over a corresponding brief interval of time the value of the applied stress. Consequently with shorter time intervals, higher stresses will be required for breakdown. The actual stress on the insulation remains approximately that of region *B*. Further light on this question might be had from oscillograms of the impulse at the moment of breakdown over the whole range of region *A*.

**F. J. Vogel** (Westinghouse Elec. and Mfg. Co., Sharon, Pa.): The author has presented a very interesting paper. The curve showing the characteristics of solid insulation from extremely short times to long times and 60 cycles is doubtless typical. I feel, however, that it may be misleading to ome engineers in the inference that it may be compared to transformer insulation in general. I would like to present some data n support of his data, and some other data to show that the values given may not be universal.

Some years ago, tests on approximately $^1/_{16}$ inch oil impregnated pressboard were made, both with alternating and continuous potentials. These tests were one minute hold tests, under oil, and they were made with square edged disks, comparable to Montsinger's tests. The average breakdown value at 60 cycles was 39 kv effective value, and with direct current 172.5 kv. The ratio between these values is almost exactly the same as obtained by Montsinger for 60 cycles and impulse voltages, and confirms his belief that the curve is flat from 3 microseconds even to 1 minute.

However, tests have also been made with square cornered disks on solid pressboard in thicknesses from single $^1/_8$ inch sheets to 3 $^1/_8$ inch sheets. The table shows the results obtained:

| Thickness of Pressboard, Inches | 60 Cycle One Min. Test Breakdown, Kv | Impulse Strength, Kv | Ratio, Impulse Strength to 60 Cycle Crest |
|---|---|---|---|
| 1—$^1/_{16}$ (approx.) | 39 | 172.5* | 3.12 |
| 1—$^1/_8$ | 55 | 180 | 2.32 |
| 2—$^1/_8$ | 84.5 | 360 | 3.02 |
| 3—$^1/_8$ | 115 | 550 | 3.38 |

* One minute d-c hold test for this value only

These data show that widely varying ratios may be obtained. Experience also shows that the materials vary quite widely as evidenced by tests made at different times. It is to be noted also that marked corona disturbances result, during tests made similarly to the above, at voltages far below the breakdown point, and that such conditions are not representative of conditions within properly designed transformers on test where the ratio between the corona voltage and breakdown voltage is high.

The writer would like to refer to the papers, "Factors Influencing the Insulation Co-ordination of Transformers," mentioned in P. L. Bellaschi's discussion. The tests described in these papers were made on models typical of practical transformers, in which the stress appears to be largely withstood by the oil, and the impulse ratio found was 2.2. It is by no means certain that the characteristics of liquid dielectrics are the same as those of solid dielectrics. There are indications that the d-c strength and impulse strength of solid insulations are about the same, but this is not true for liquid dielectrics. These facts indicate that Montsinger's curve may not be representative for transformer insulation, either for the impulse ratio or the shape of the curve.

**Herman Halperin** (Commonwealth Edison Co., Chicago, Ill.): In *Archiv für Elektrotechnik*, v. 23, 1929, p. 305–22, Reinhard Jost reports the results of similar investigations of "The Breakdown Strength of Some Solid Insulating Materials for Voltage Applications from Long to Very Short Duration." The tests covered surge, a-c, and d-c tests and included durations from $10^{-9}$ to $10^{+4}$ seconds or from 0.001 microsecond to $2^3/_4$ hours. Pressboard tested in air and in oil was among the materials studied.

Jost found a region of constant breakdown voltage from about $10^{-7}$ to $10^{-1}$ seconds or from 0.1 to $10^5$ microseconds. The upper limit of time agrees quite well with Montsinger's results, while the lower limit is much lower than in Montsinger's test. Although, otherwise, there is disagreement between the test results, probably the result of different test conditions, it is interesting that Jost also finds 3 regions of breakdown for pressboard.

In connection with extensive breakdown tests on cable insulation over a period of years, it has been found that the relation of voltage to time may be best expressed as merely an inverse exponential function of the time. Montsinger's formula, which is similar to Peek's, has a constant indicating minimum breakdown voltage in addition to the effect of time.

I presume from the fact that Montsinger indicates in his paper that he is giving merely a progress report that further test data will be made available at a later date. It would be of interest to see data obtained on insulations simulating actual construction details of equipment, such as, for example, those reported by F. J. Vogel on transformer insulation. Some of Vogel's data presented at the 1935 high tension conference in Paris and accompanying this discussion show good agreement between impulse ratios, provided those determined from the present data are arbitrarily calculated as the ratio of surge breakdown to about the 8-second breakdown values:

| Time Lag, μ sec | Impulse Ratio | | | |
|---|---|---|---|---|
| | Vogel Simulated Trans. Insulation | | | Montsinger $^1/_{16}$ Inch Pressboard |
| | Shell Type | Core Type | Interleaved Barriers | |
| 0.5 | | 3.0 | | 3.04 |
| 1 | 2.65 | 2.2 | | 2.64 |
| 2 | 2.3 | 2.13 | | 2.32 |
| More than 2 | 2.25 | 2.1 | 2.3 | 2.23 |

This brings up the question of what value to use as the 60 cycle breakdown voltage in calculating impulse ratio. As indicated by the *C* region of the curve, this value may vary over a wide range, and it appears essential to assign a definite time value to the 60 cycle breakdown voltage used in determining impulse ratio, at least for solid insulations. Also, some correlation should exist between impulse ratios for solid insulations and air gaps, for co-ordination purposes.

Further study along these lines appears desirable.

According to the paper, the test breakdowns in region *A* were all on the front of the wave. If on the contrary, tests were made to determine minimum breakdown voltages, the time lag factor would be involved. It would be of interest to learn if breakdowns occurring on the tail of the wave would give results falling on a curve similar to that shown in the paper.

**V. M. Montsinger:** I am glad that Herman Halperin has called attention to the Jost article of which I was not aware. A review of this article reveals that no test points are shown within the time ranging from about 8 microseconds to 1 second. The flat part of Jost's curves over the large gap in time, approximately $10^6$ microseconds, apparently was based either upon test points not shown on the curves or upon an assumption.

I would like to emphasize, as I did in the presentation, that the main object of my investigation was to obtain data on the breakdown strength of insulation within the *B* region, that is, to see if the breakdown strength remained constant over a long period of time, as some preliminary tests indicated it would. Regions *A* and *C* had already been well explored.

Halperin brings up the point of what 60 cycle time of breakdown to use in obtaining the impulse ratio of insulation. Although there are some good reasons why we should use shorter than one minute breakdown values, yet, due to the difficulty in obtaining reliable low frequency breakdown values for times less than one minute, I feel that the one minute (or its equivalent as recommended by A.S.T.M.) value must be used, as it is the only way to make tests on large and expensive insulation setups where a volt-time curve is not practical.

In connection with Halperin's point about breakdown on the wave tail, as pointed out in the paper, solid insulation (or solid and oil in series) seldom will break down beyond the crest. The reason for this peculiar behavior of a solid as contrasted with oil and air is not known.

F. J. Vogel questions whether the impulse ratio is representative for transformer insulations. It may not be. I do not attach very much importance to either the shape of the 60 cycle curve or to the impulse ratio, the object being to determine the extent of the time for the constant voltage breakdown portion of the curve (region *B*). The 60 cycle test points were merely given to show the contrast in the shape of the curves in the 3 regions.

Vogel also questions whether the general shape of the curve is representative of transformer insulation. This is an important point. Most of the vital insulations in a transformer consist of either solid (as used between turns) or solid and oil in series (as used between coils and between windings), oil alone seldom being used in small vital spaces. The insulation used for these tests represents the turn to turn insulation in a transformer.

The next question is: Does it represent solid and oil in series? Numerous tests show that solid insulation acts quite like solid and oil in series within regions *A* and *C*. For example, figure 4 of this discussion shows that there is very close agreement between Vogel's and my tests made on solid and oil in series and the tests shown in the paper on $^1/_{16}$ inch pressboard within region *A*.

Likewise the 60-cycle volt-time curves given in reference 4 of the paper show that the shape of the curves is similar; compare figures 11 and 12 with figures 19 and 21, the first 2 being for pressboard alone and the latter 2 being for pressboard and oil in series.

Since a solid has volt-time characteristics quite like solid and oil in series for regions *A* and *C*, it is not very likely that it will show different characteristics for region *B*. In other words, I would expect the insulation network in a transformer to have a long-time constant-voltage breakdown strength similar to that shown in region *B* for solid insulations.

I was, of course, pleased to know that the tests of P. L. Bellaschi and W. L. Teague confirmed my own so closely under similar test conditions. Another significant point brought out in their findings is that apparently the edge effect was not so great as I supposed for region *A* since a good portion of their breaks were not at the edge of the sharp edged electrode but at points distributed over the electrode area.

I am at a loss to understand why Bellaschi and Teague did not get an increase in breakdown voltage in region *A* for very short time intervals of less than 2 or 3 microseconds. Both Vogel's and my tests (as shown in fig. 4) as well as Jost's tests show that there is a decided increase in strength for short time intervals. It should, of course, be understood that these data represent single shot strength. Repeated shots with steep front waves apparently do not show as great an increase in breakdown strength over repeated shots with slow front waves, as shown in my curve.

C. F. Hill, I feel, is mistaken in ascribing the flatness of the *B* region to a distorted scale (logarithmic) rather than to an actual flatness. Relatively speaking, from 3 microseconds to 50,000 or 100,000 microseconds is a long time and it includes an important range of time under certain types of surges obtained in service, particularly switching surges. To me, one of the most important points is that apparently the breakdown strength of transformer insulation is the same for switching surges as for impulse voltages of 3 microseconds and longer. It indicates that switching surges are probably not as dangerous as we have considered them to be. Bellaschi's tests bear this out.

It was not intended to show that the transition from region *A* to *B* and from *B* to *C* was discontinuous. I agree that it should be gradual even though the time element involved is short.

The pressboard used was given standard vacuum drying and oil impregnated for 4 hours before breaking the vacuum. The material used for the 3 regions was all prepared and treated at the same time so that the uniformity was as good as can be obtained from a given batch of material.

Regarding Hill's theory that the *A* region may be explained by the oil in the pressboard, he may be right. Anyway this is a condition that is present in all oil immersed transformer insulations.

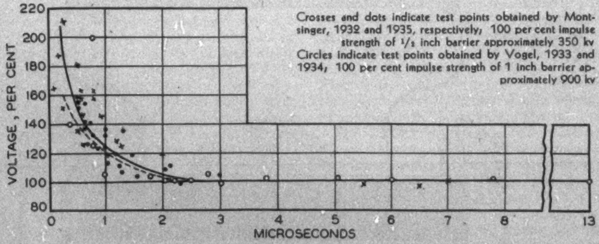
I fully agree that it would be interesting to use continuous potentials for all 3 regions but this test should be made with a type of electrode that produces a uniform dielectric field as the object is to determine the characteristics of a true solid rather than insulation as used in transformers.

Regarding J. B. Whitehead's statement that the tests do not represent the inherent characteristics of solid insulation, it is pointed out in the paper that a sharp edged electrode was purposely used to have the tests represent the most severe case that may occur in a transformer structure, and that to study the material as a material, a uniform dielectric field should be used.

In reference to his criticism of the accuracy of the quadratic law, my experience with many volt-time curves made on all kinds of solid insulation indicates that this formula fits the curves closer than any other formula.

My reason for mentioning the 3 regions found by Moon and Norcross was not because I think there is any relationship between the phenomena found in the 2 investigations.

Whitehead questions the increased breakdown values in *A* region when the tests are made limiting the breakdown to properties of the material. A reference to the article by Jost (mentioned by Halperin) who apparently made some tests in a uniform field, will show that Jost found a decided upturn in all of his curves. I feel that there is an *A* region even when the breakdown is limited to properties of the material. It is true that the duration of the time in Jost's *A* region is shorter than 3 microseconds, but his tests indicated that there is an *A* region for a material when tested as a material only.



Crosses and dots indicate test points obtained by Montsinger, 1932 and 1935, respectively; 100 per cent impulse strength of $^1/_8$ inch barrier approximately 350 kv
Circles indicate test points obtained by Vogel, 1933 and 1934; 100 per cent impulse strength of 1 inch barrier approximately 900 kv

**Fig. 4. Voltage-time curves of insulation barriers of pressboard and oil in series (solid curve) and $^1/_{16}$ inch pressboard sheet (dashed curve)**

# Vibratorily Commutated Stationary Conversion

**Discussion and author's closure of a paper by G. T. Southgate published in the November 1935 issue, pages 1213–21, and presented for oral discussion at the electrical machinery session of the winter convention, New York, N. Y., January 29, 1936.**

**J. J. Linebaugh** (General Electric Co., Schenectady, N. Y.): The author has devised a very interesting stationary mechanical rectifier different in many respects from the usual mechanical rectifier and one that should be capable of taking care of an appreciable load.

The various designs mentioned indicate that the apparatus is not limited to only one form, but arrangement of the component parts can be changed to suit special requirements such as voltage, current, or type of current carrying parts.

The great difficulty in building mechanical rectifiers for capacity greater than a few amperes has always been sparking at the contacts when making and breaking contact in commutating the different circuits. The author has overcome this difficulty by using a special transformer designed so that it has practically no reactance to retard or accelerate the flow of current at different load currents. It would seem that the success or failure of the proposed rectifier would depend on being able to produce a transformer with the characteristics desired. This may be quite difficult for the larger sizes.

The general design seems to be well adapted to the conversion of high continuous voltages. The usual carbon and copper dust from rotating parts would not be present and it should be easy to insulate the different bars or conductors from ground and each other by providing insulating barriers and suitable creepage distances.

It has been my experience that it is extremely difficult to design commutating equipment which will make and break circuits of this kind and it is hoped that the author has solved this difficult problem.

The development of a suitable size unit and operation for some time under actual working conditions will be necessary to demonstrate the commercial practicability of the equipment described, and it is hoped that this can be done shortly.

**H. W. Anderson** (Iowa State College, Ames): This very interesting machine seems to be capable of representation as a rotary converter with a stationary armature and commutator, and with a moving field and brush structure, but lacking linkages with a field circuit and having essentially no moving mass. The elimination of field circuit linkages and rotating mass certainly should account for a considerable difference between its transient characteristics and those of an ordinary rotary converter.

Though the author has handled the details of mechanical contacts in a very thorough way, this machine as a converter appears to be well adapted to the use of grid controlled rectifier tubes. Any desired phase relations for grid control can be secured from windings already available. The discharge in each tube would be automatically extinguished as the flow of current is transferred to a succeeding tube. This converter, so arranged with tubes, could be compared to an ordinary polyphase converter using hot-cathode mercury vapor tubes in something like the way that a closed-circuit bipolar d-c armature might be compared to a now-historical open-circuit armature.

Southgate's machine has as inherent advantage over ordinary contacting converters. Each cycle is subdivided sufficiently so that external circuit parameters have rather little influence on wave shape.

**C. C. Herskind** (General Electric Co., Schenectady, N. Y.): The vibratorily commutated converter is a very ingenious and interesting device. If it proves practical it will be a direct competitor of the mercury arc rectifier and the synchronous converter. The high efficiency would seem to favor its application, particularly in the low voltage field, that is, below 600 volts.

There seems to be no question that this converter will operate in the manner described under steady load conditions. However, in order to be practical, the apparatus must be capable of operating under unbalanced and transient conditions. For example, a mercury arc rectifier with one anode circuit broken will still operate on 11 anodes, although at reduced rating. Similarly, a synchronous converter will operate with some of the brushes disconnected. What would happen in case one of the vibrators failed in the conversion apparatus?

Some of the transient conditions which will be encountered in service are: starting, d-c short circuits, reduced supply voltages, variations in frequency, and single phase operation. What will be the effect of these transient conditions upon the commutation at the vibratory contacts and how will the amplitude and phase relations of the vibrator be affected by these transient conditions? In the case of failure and arc-over of one of the vibratory contacts, what means must be provided for clearing the conversion unit from the power system, to prevent its destruction?

The paper proposes the use of the conversion unit for d-c to d-c transformation. When the unit is so used, some means must be provided for supplying the magnetizing current required to set up the flux in the transformer core, as this magnetizing current cannot be supplied from the d-c system. What means are proposed for supplying this magnetizing current?

What is the current capacity of the vibrating contacts? Judging from experience with contactors, it would seem that the current capacity of a single contact cannot be indefinitely increased by increasing its area because of the effect of localized heating and local action on the contact surfaces.

The conversion apparatus described in this paper would seem to possess an important advantage over other types of conversion equipment because of its static nature, and the absence of auxiliaries. The compactness of this conversion unit should effect a considerable reduction in installation costs.

**G. T. Southgate**: In his examination of the converter's principles, J. J. Linebaugh correctly deduces the freedom of design and function that is contributed by the vibratory commutation. Likewise operative testing, particularly with the revealing oscillograph and temperature explorers, is greatly facilitated by the nonrotary accessibility of the inductive, insulative, and commutative parts.

For moderate and low voltages, the construction of a transformer with the desired minimal flux leakage is accomplished by the close spacing of flat form-wound primary and secondary coils in the same core slots. If at higher voltages the coil separation might otherwise be sufficient to introduce appreciable reactance, such leakage is ef-

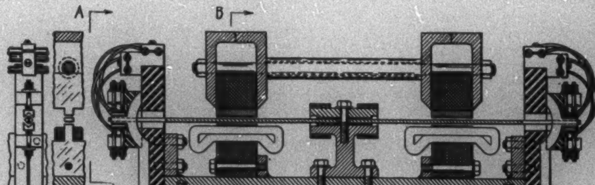


Fig. 1. Diagram showing flat mounting of the commutative system

fectively reduced by the inherent feature that the windings are much subdivided for the multiple phasing. This sectionalizing has the same leakage-decreasing effect where it is practiced in ordinary transformers for reduction of voltage per coil, in amount proportional to from the first to the second power of the subdividing. ("The Magnetic Circuit" (a book) V. Karapetoff. McGraw-Hill, 1911, p. 213–14.) Leakage can be reduced further by employing high strength and correspondingly thin insulation between coils. Finally, for extreme cases the high voltage turns can be enclosed within hollow low tension conductors, more easily in manufacture than they were in the model.

In addition to this flux-leakless transformer condition, good commutation does indeed require that the making and breaking of contact be timed precisely enough. For such sequence, the employment of mechanical actions other than the familiar ones of rotation may seem radical. Yet it is to be recalled that there has long been broadly exploited a branch of electromagnetic vibratory mechanics of delicacy incomparably greater than that required in the commutative contacting. Telephonic and particularly loud-speaker kinetics exemplifies far more disciplined collaboration of extreme variables, willing and willful. The frequencies and their amplitudes are almost infinite in number; resonance may be a service as it is in vibratory commutation, but can be an acoustic evil.

In the new commutator the vibrators, mechanically tuned to the one electric frequency, are rigidly united in faithful cooperation. The mechanics of vibrating systems, especially the simpler and vibration-exploited forms, is accurately determinate. ("Vibration Problems in Engineering" (a book) S. Timoshenko. Van Nostrand, 1928. A shorter analysis by the same author is given in Marks' Mechanical Engineers' Handbook, McGraw-Hill, 1930, p. 489–502.) Critical examination is invited rather to the more practical cantilever form of the reeds than to the earlier xylophone mounting. The later assembly adds to the unchanging elastic properties of low-stressed steel the rigid stability of clamped support, simplifies the construction, and facilitates the variation of combinations from unitary elements. As an example, the reed-and-contact system may be mounted above the transformer flatwise instead of cylindrically, with resultant improvement in compactness. This is shown in figure 1 of this discussion.

In the transformer, further simplified design eliminates all punching of the core slots by the employment on each side of 2 thin magnetic gaps instead of one, and of plain rectangular strips for the intervening teeth. These are economies not only for manufacture but also for the further demonstration suggested by Linebaugh. With these strips and with form-wound stock coils the assembling of a transformer may be made as unitary as that of the commutative system.

H. W. Anderson's comparison of the machine with a rotary converter leads to the somewhat closer analogy of the dynamotor. When stripped of moving mass and of linkage with a d-c magnetic field as he properly stipulates, either picture becomes practically that of the polyphase transformer with commutation (which must be dual). The transients particularly take on the simpler characteristics belonging to a transformer. The simultaneous primary-secondary short-circuiting that makes the commutation operative isolates the commutated winding elements from the external circuit parameters. The noninfluence of the last upon wave shape is one of the degrees of freedom from reactance, reflecting the converter's simplicity in terms of $i = e/R$, that is further appreciated in view of Anderson's reference. Relations of this machine's transients to those of rotary machines are considered below, among those brought forward by C. C. Herskind.

Use of electronic tubes had been considered, and discussed in the author's correspondence. It is workable in suitable form and may prove advantageous for high voltages and large powers. Replacement of solid contacting by vapor conduction would introduce the voltage drop that is the limitation upon the efficiency of vapor rectifiers applied to lower voltages. At all voltages for power outputs not less than a kilowatt the costs of vibratory contacting elements should be far below those of electronic tubes, original and replacement.

In distinction from rectification, commutation of closed windings employs the contacting elements only from 10 to 15 per cent of the time. As in the case of rotary commutation, we can afford to have the segments so briefly active, because they are then worked at such high current densities as to require the intervening cooling, and because they are simple metal blocks of relatively small size and investment. But technological unemployment of hot-cathode vapor rectifiers during 85 per cent of the time might prove expensive.

C. C. Herskind pertinently observes that for satisfactory service the machine must continue to function during or immediately after certain transient conditions. In comparison with a synchronous converter or synchronous motor generator set the stationary type has no rotary armature to engage in hunting from inherent or external causes, hence no corresponding danger of dropping out or flashing over. If the supply feeder should swing rapidly because of a hunting load elsewhere, the commutation would be mildly affected; but the machine would not contribute to the swinging.

As in a vapor rectifier with an anode idle or a multipolar rotary converter with a brush removed, the stationary converter would function with a contact stilled or disconnected, provided the conditions be made comparable. That is to say, in a vibratory converter big enough to be wound multipolar and multipath, the other paths would assume the burden, at reduced total rating. Even in a bipolar machine there is normally division among 3 contacts at a "brush position"; and 2 left alone could carry on, over-loaded but with no space-serial neighbor to which sparks (if any) could be contagiously passed.

The starting transient is that of an ordinary transformer. If residual magnetism and initial voltage conspire to produce a starting rush, it is only that of exciting current through the 3-phase leads. The commutators are innocent of its occurrence, and no flashover or sparking results. If the machine is operating as a d-c to d-c transformer, its excitation is still supplied through separate polyphase leads.

For secondary (direct current) or internal short circuit the machine should be provided with a primary breaker, which may be reclosing, as in the case of an a-c transformer. Since the machine does not have to be accelerated and synchronized on restarting, the main objection to primary breaking is removed. The breaker should not disconnect the commutative actuator, which should continue to drive the reeds in the interim. For the larger jobs there may be provided current-limiting reactors in the primary leads, collaborating with the overload switch. They limit the rush not only directly but, because of the slight inertia of the reeds, also by throwing the commutation out of phase instantly and for the brief period before the opening of the power switch. If desired, an input-output power differential relay can be employed. These provisions seem ample to protect the secondary system, the converter including its output commutator, and the primary system.

Reduction of a-c voltage has less than proportional effect upon the vibration amplitude of the reeds and, for practical ranges, need have none at all upon the commutative contacting period. The design is such that the reed-mounted members overswing considerably, and break contact at timing limited by the return stroke of the other or "passive" members.

As to frequency variation, the curve of amplitude of response of reeds can be made rather flat for some distance either side of resonance. ("Alternating Current Rectification and Allied Problems" (a book) L. B. W. Jolley. John Wiley and Sons, 1928, p. 147.) The author found in this development that reeds that sang naturally at 65 cycles could easily be driven at 60 cycles. The temperature coefficient of frequency of an unloaded steel fork or reed has been found by measurement to be minus 0.000112 per degree centigrade. ("Theory of Sound" (a book) Lord Rayleigh. Macmillan, 1926, v. I, p. 86.) For an end loaded reed it is less by a strong function of the mass of the load. Hence for an extreme assumption of 80 degrees centigrade rise, the resonance frequency of reeds designed for 60 cycles could be lowered less than half a cycle.

Single phase operation, intended for emergency, may be considered jointly with d-c to d-c transformation. For either performance, polyphase excitation must be provided. The transformer primary may be arranged for 3 phase supply and, if only single phase current is available, capacitive and inductive circuits may be branched to supply 2 of the phases. In cases justifying provision against 3 phase circuits "going single phase," such arrangements or others could be included. With d-c input a small motor generator can be provided for transformer and actuator excitation, with or without capacitive assistance.

The current capacity of vibrating contacts firmly meeting may be put safely at 400 amperes per square inch with natural cooling, and this value may be considerably raised by ventilation. It is true that the capacity of an individual member cannot be increased indefinitely by enlarging its area. Ordinarily, the larger the faces the less perfect is their contacting on every square millimeter. Yet extremely large areas, backed by the resiliently laminated bridge, are successfully employed in the classic case of the air circuit breaker, and especially so with its modern silver plating. Subdivision, including lamination, is a natural design tendency in the vibratory converter; and resiliently floating contact support is an easy form.

Localized heating of the faces is largely caused by the negative temperature coefficient of contact resistance which, in turn, is usually a property of the oxide film on most metals as they become heated in air. The most universal noble contact metal, silver, has this property in far less degree. Alternatively, the contacts may be immersed in nonoxidizing and otherwise benefactive gas, nitrogen, helium, or hydrogen, in which case copper will serve for the metal.

The author shares Herskind's view classifying the machine as a potential competitor of the mercury arc rectifier, the synchronous converter, and the motor generator, adapted especially and initially to the voltage range of 600 and downward. This is considered without prejudice to its future development also for higher voltages, to which it is adaptable by series internal connection. Its static nature, self-completeness, compactness, low installation cost, and nonattendance are emphasized as major advantages.

Regarding noise made by the apparatus, in the open air it is a buzzing, considerably louder than the hum of an a-c transformer but much less than the commutative scream of a rotary converter. Obviously, the new converter should be enclosed, with the transformer portion ordinarily immersed in oil or other insulating liquid.

A correction in the bibliography of the paper should be noted. Reference 7 should be "Use of the Noble Metals for Electrical Contacts," by E. F. Kingsbury. (A.I.M.E. *Tech. Pub.* No. 98, 1928, instead of No. 95, another title.)

# Electrical Brush Wear

**Discussion and author's closure of a paper by V. P. Hessler published in the October 1935 issue, pages 1050–4, and presented for oral discussion at the electrical machinery session of the winter convention, New York, N. Y., January 29, 1936.**

**R. E. Hellmund** (Westinghouse Elec. and Mfg. Co., E. Pittsburgh, Pa.): It has been pointed out by others that the various phenomena observed in sliding contacts on a commutator are materially different from those observed in such contacts on slip rings. It is therefore quite probable that marked differences also exist between the wear of brushes on slip rings and those on commutators. This is to be expected because in commutators there is usually some sparking and consequent burning of material in addition to the mechanical wear. This sparking may or may not be an important factor. I had occasion to observe this in a test made some time ago in which a slip ring and brushes were subjected to vibration with low and high current densities. Sparking was visible under both conditions of load. Although the wear under light load was almost negligible, it was quite appreciable under full load conditions.

There is much evidence in this paper that even in slip rings with steady current there are a great many variables that are difficult to control and evaluate, and it is therefore quite natural that investigators of this wear problem are not anxious to introduce additional variables. Nevertheless, the greater proportion of applications of sliding contacts is in connection with commutators, which makes it very desirable from a practical point of view that the investigations be extended to include phenomena applying to commutators.

The most apparent reasons for the difference between the commutator and slip ring applications are: (1) The slotting of the commutator and other irregularities may introduce mechanical conditions different from those applying to slip rings; and (2) the current density in the sliding contact of commutators varies continuously over wide ranges. Possibly it might be well to inject these conditions one at a time into investigations as described by Hessler as this will permit a more correct analysis than the inclusion of both conditions at the same time. As a first step, it might therefore be suggested that the wear on smooth slip rings be investigated with continuously and suddenly changing current densities. This would have the further advantage that the variations could be definitely recorded by the oscillograph and modified at will, which would not be possible on a commutator in actual service. An arrangement of electronic devices such as described in the paper "Sparking Under Brushes of Commutator Machines" (R. E. Hellmund and L. R. Ludwig, ELEC. ENGG., v. 54, March 1935, p. 315–21) might be used for this purpose and give valuable basic information.

**R. M. Baker** (Westinghouse Elec. and Mfg. Co., E. Pittsburgh, Pa.): I think the author is to be commended on the painstaking effort which he has made to obtain information on a subject which is so important to the understanding and overcoming of the many difficulties associated with the operation of sliding contacts, an effort in which he has tried to eliminate as many of the variables as possible. It seems to the writer that about all that can be said at present of test data obtained on the performance of carbon brushes, whether interest is primarily in brush wear or in electrical performance, is that the results obtained are characteristic of the apparatus on which the tests were made and upon the procedure of tests. If the size of brush, the type of brushholder, the nature of the ring material, the degree of mechanical perfection in the apparatus, the finish of the ring surface, the diameter of the rings, the speed of rotation, the number of brushes operating in parallel, the duration of the test, or any one of a number of other unknown factors is changed, it is very probable that the results of the test will be altered. It is also known that the dust content, the moisture content, and the temperature of the atmosphere around the contacts, as well as the chemical composition and purity of this atmosphere, can produce equally large variations in results obtained. Hessler took measures to eliminate these latter variables as far as possible.

While the author maintained the absolute humidity essentially constant throughout the series of experiments, it is well to notice that the value maintained (about 14 grains per cubic foot) is a little higher than that occurring normally even on the most humid summer days. This fact may partly explain the exaggerated polarity effect observed in most of his data. I believe that some later work by him indicates this to be the case.

It would seem that the greatest factor of uncertainty in this series of tests is the shape of brush, and the type of brush holder used. A long narrow brush is naturally unstable and subject to chatter; especially when used in a radial holder. This is a point which I feel should be checked by repeating some of the tests with a low flat brush or with some other arrangement which insures continuous contact between the brush and the ring.

Regarding the large polarity effect observed, it is the writer's experience that for carbon brushes, as well as for metal graphite brushes, the brush wear is usually greater where the brushes are negative in the motor sense, but the ratio is seldom found to be more than 2 to 1, and in many cases is much less. True, all of the tests made by the writer have used larger brushes, and there was always more than one brush per ring. The rate of wear found by Hessler for the negative metal graphite brushes is about normal, but the wear on the positive brushes is phenomenally high. The constant rate of brush wear for the negative metal graphite brushes for all values of current is definitely contrary to the writer's experience. In some recent tests cases were observed where the rate of brush wear at 110 amperes per square inch was 6 or more times greater than the rate of wear at zero current. These tests were made on large copper-alloy rings with 4 brushes per ring, operating in air with an absolute humidity of about 3.5 grains per cubic foot.

It is to be hoped that Hessler will continue this investigation, gradually changing the conditions of test until he is able to draw general conclusions as to what rate of brush wear may be expected under various operating conditions. This would be an achievement of great practical value, and when this point is reached it should be possible to interpret the results in terms of fundamental phenomena, and the process of brush wear in sliding contacts will most probably be entirely understood.

**M. S. May** (Speer Carbon Co., St. Mary's, Pa.): I can sympathize with the author when he is criticized because his test methods do not duplicate service methods. However, I want to call attention to one additional difference between his methods and operation conditions. In his test the positive and negative brushes do not trail each other but run in separate tracks. This permits the brushes of opposite polarities to build up different types of commutator surfaces, which condition would not prevail in actual operation.

The point in the paper which most impressed me was the difference between the metal and nonmetal grades of brushes. In the case of the metal grades, the positive brushes wore very much faster than the negative. In the case of the carbon grades, the reverse was true. I am wondering whether this might be partially explained by some tests which have been made on disks for rheostats.

It was found that a pile of such carbon disks, copper plated on one side, showed an increased resistance as compared with the unplated disks, doubtless due to the oxide film. It was also observed that such a pile showed a higher resistance when the current flowed in one direction in relation to the copper coating than when it flowed in the opposite direction. The interesting point, however, was that the carbon disks showed a very decided increase in contact resistance from copper coating, whereas disks from the metal graphite brush grades showed a distinct drop in contact resistance from copper coating.

**V. P. Hessler:** The author quite agrees with R. E. Hellmund that the investigations should be extended to include the effects of commutation as soon as possible. Both slip rings and commutators were considered before starting the investigation It was considered that since there was no fundamental information available concerning the effect of current density upon electrical brush wear it would be desirable to operate under controllable current density conditions. Also the results on a commutating machine would have been dependent upon the quality of commutation. The author has not yet found a method of expressing the quality of commutation quantitatively.

The author has already conducted some tests upon slip rings with an alternating current superimposed upon direct current. Further investigation upon slip rings with suddenly changing current densities as suggested by Hellmund should be instructive.

The mechanical abrasion effect of a commutator as compared to slip rings could be investigated with the aid of a commutator having all bars short-circuited. Such an arrangement would eliminate short-circuit current difficulties and give results which could be compared quantitatively with slip ring operation.

R. M. Baker's statement that the results obtained are characteristic of the apparatus on which the tests were made and upon the procedure of the test is quite correct. The investigations reported in this paper represent only a small portion of those conducted by the author. (See "The Effect of Various Operating Conditions Upon Electrical Brush Wear and Contact Drop," Bulletin 122, Iowa Engineering Experiment Station.) However, all of the results obtained uphold the particular conclusions reached in this paper. The numerical value of the wear does change with the variables suggested by Baker.

A brush of larger cross section would have been preferred except for the additional cost of power for circulating current. The radial type of holder was chosen to facilitate measuring the brush wear. It is possible to measure the length of a square end brush with much greater accuracy than a beveled brush. The brush boxes were made very accurately and were set very close to the ring. Audible chatter has occurred only on very rare occasions during the 4 years the tests have been in progress.

M. S. May's statement concerning trailing and nontrailing brushes is very important. No investigations of trailing brushes had been made by the author at the time of writing this paper. Such investigations have since been made with distinctly different results. The conclusions reached in this paper must be considered to apply to the case of positive and negative brushes operating upon separate paths.

## A Static Thermionic Tube Frequency Changer

**Discussion and authors' closure of a paper by A. Schmidt, Jr., and R. C. Griffith published in the October 1935 issue, pages 1063–7, and presented for oral discussion at the electrical machinery session of the winter convention, New York, N. Y., January 29, 1936.**

**R. E. Hellmund** (Westinghouse Elec. and Mfg. Co., E. Pittsburgh, Pa.): Many thermionic tube arrangements have been proposed in Europe for use in changing from one frequency to another without an intermediate d-c circuit. The difference in the various circuits proposed is chiefly the number and arrangement of the tubes, so that without using an unduly large number of them the desired wave shapes may be obtained with a minimum outlay for transformers and filtering equipment. In all these European arrangements there is, however, one favorable factor, their standard frequencies of 50 cycles for general power circuits and $16^{2}/_{3}$ cycles for railway work result in an integral conversion ratio of 3 to 1.

With the standard frequencies used in the United States, direct conversion with any of the possibilities known to me would result in a continuously changing pattern of voltage and current waves, which in turn would make the problem of filtering equipment very difficult. However, in a few instances there may be special conditions such as described in the paper under which the application of such direct conversion arrangements will be justified. I should like to know if the authors agree with these statements.

**C. C. Herskind** (General Electric Co., Schenectady, N. Y.): Mercury arc rectifiers have been used for some time and their characteristics are quite well known. With the development of control grids, the use of rectifiers for other purposes than straight rectification was proposed; one of these proposed uses is that of frequency changing.

Static frequency changer circuits may be divided into 2 general types. The first type is that in which a rectifier and inverter are connected in series with a d-c link between them, and is similar to many of the proposed schemes for d-c transmission. The other type has been termed by some the composite type of circuit, in that the same anode performs the dual functions of rectification and inversion. Two of the fundamental problems which must be solved in order that these circuits may be successful are commutation and wave form. It would seem that the rectifier-inverter type of circuit would have the better wave form as the pulsations in one network are not carried over into the other network because of the d-c link connecting the rectifier and inverter, whereas in the case of the composite type of circuit no wave smoothing element is provided. The composite type of circuit would seem to possess some advantages with regard to commutation, particularly in the case where the output frequency is lower than that of the input, as commutation may be effected from the input system, while in the case of the rectifier-inverter type of circuit some means must be provided for commutating the inverter. Furthermore, a frequency changer using the composite type of circuit will be lower in cost than one using a rectifier-inverter. At the present time it cannot be decided which type of circuit is superior, but the installation described in this paper will furnish a basis for the determination of the merits of the composite type. This frequency changer, which I believe is the first unit of its type in commercial service in the United States, has been in successful operation for approximately a year.

**A. Schmidt, Jr., and R. C. Griffith:** It is generally possible to obtain with a static frequency changer any frequency ratio which would result from the use of a synchronous motor generator set. For instance, the use of a 4 phase input transformer connection, with 4 anodes firing during each output half cycle, would result in a frequency ratio of 60 to 24, and a 10 phase input transformer connection, which may be obtained by zigzagging the transformer secondary windings, will give a frequency ratio of 60 to 25 if 8 anodes are fired during each output half cycle.

Asynchronous operation with any circuit arrangement would result in a changing pattern of voltage and current waves, as has been suggested. This will be equally true with synchronous ratios of 3 to 1 or any other value.

## The Compensated Thermocouple Ammeter

**Discussion and author's closure of a paper by W. N. Goodwin, Jr., published in the January 1936 issue, pages 23–33, and presented for oral discussion at the instruments and measurements session of the winter convention, New York, N. Y., January 28, 1936.**

**J. H. Miller** (Weston Electrical Instrument Corp., Newark, N. J.): The electrothermic ammeter, such as that described in this paper, has negligible errors at frequencies considerably higher than the so-called broadcast band. For extremely high frequencies, however, the skin effect and other errors begin to be of importance despite the design of the heating conductor.

The most important error at extremely high frequencies is that of the increase in the effective resistance of the heated conductor, due to skin effect. Taking equation 19 from this paper, we can substitute for the actual resistance of the heater strip times its dimensions or

$$\rho = \frac{Ra}{L} \tag{1}$$

which gives the original equation in the form

$$(\theta_1 - T_0) = \frac{I^2R^2L}{8kRa} \tag{2}$$

Canceling through,

$$(\theta_1 - T_1) = \frac{I^2RL}{8ka} \tag{3}$$

It may be noted that the temperature rise of the strip is proportional to the square of the current and directly to the resistance. If the effective resistance increases because of skin effect, a greater amount of heat will be developed, the temperature of the strip will rise, and in a complete instrument the reading will be higher than for the same current at a lower frequency.

Assuming a standard instrument, that is, one calibrated at low frequency, the error caused by an increase in effective resistance due to skin effect at high frequency may be determined. Let $R_1$ be the effective resistance at the high frequency under consideration, and put in a sufficient current at low frequency and then at high frequency to give the same indication on the instrument or the same strip temperature; let the true effective current at high frequency be $I_1$.

Then the 2 values may be equated as follows:

$$\frac{I^2RL}{8ka} = \frac{I_1^2R_1L}{8ka} \tag{4}$$

or

$$I^2R = I_1^2R_1 \tag{5}$$

then

$$\frac{I_1^2}{I^2} = \frac{R}{R_1} \tag{6}$$

and

$$\frac{I_1}{I} = \sqrt{\frac{R}{R_1}} \tag{7}$$

This shows that the true high frequency current in terms of a calibration at low frequency is equal to the square root of the ratio of the resistance at low frequency to that at high frequency. The ratio of high-frequency resistance to low-frequency resistance of a wire of a given size and material is given in tabular form in various handbooks. At a frequency of 100 megacycles, as an example, the resistance of an 11 mil platinum alloy wire is 2.57 times that at low frequencies. The square root of the reciprocal of this figure is 0.624. An instrument using such a heater wire will, therefore, give an indication that is too high at 100 megacycles, and the true current will be 62.4 per cent of the indication.

The above is predicated on the assumption that the skin effect error is the only error appearing. It is, of course, necessary that capacitances shunting the heater strip be kept small and this usually can be done. It should be pointed out that the capacitive current will be in quadrature with the heater current and may, therefore, rise to a value of 10 per cent of the heater current before the error it causes will become greater than 0.5 per cent.

There are other minor errors which may enter, and it should be pointed out that in the calculation of the high frequency resistance ratio it is necessary to use the resistance of the heater strip or wire at its operating temperature, since this ratio changes with the actual resistance for a given size and material.

When all of these factors are taken into consideration, excellent checks may be made through the use of comparison methods using very fine filaments in which the skin effect is small.

It appears, therefore, that the compensated thermoelectric ammeter is quite useful for measuring currents of extremely high frequency when adjustment of the readings is made for the skin effect in the heater for the frequency being used, and when the design is such that capacitance and proximity effects are of a low order.

**J. H. Goss** (General Electric Co., W. Lynn, Mass.): The author has developed the equations for heat flow in thermocouples and shunts and has shown how it is possible to utilize the temperature difference between the center of the heater wire and the terminals or compensators for the measurement of current.

There are certain other considerations that must be taken into account when designing a thermocouple from available materials. A short discussion of some of the errors that must be kept to a minimum by careful design might be of value.

The temperature - electromotive force characteristics of thermocouple materials generally used are reasonably linear over a limited temperature range. Assume that the electromotive force generated per degree temperature rise increases after a given temperature is exceeded. An instrument calibrated for one ambient temperature or self-heating temperature would, if the ambient rise moved the operating point off the linear portion of the thermocouple characteristic to the nonlinear portion, read slightly different from its original calibration. This is shown graphically in figure 1 of this discussion. It should be remembered that the measurement of current with the thermocouple depends only upon the temperature differential $(\theta_1 - T_0)$ and not on the actual temperatures of the hot and cold junctions.

This effect may, of course, be reduced or eliminated by designing the couple to operate well within the linear portion of the curve, or by using materials with a wider linear range. Instrument sensitivity and heater-wire life are 2 practical limitations that govern the choice of materials and the point of operation on the temperature-electromotive force characteristic curve.

There are 2 other effects that may enter into the final error and tend to offset the positive error previously assumed. Equation 19 of the paper shows that for a simple thermocouple with both blocks at the same temperature,

$$(\theta_1 - T_0) = \frac{(I^2R^2)}{8K\rho}$$

This equation may be written

$$(\theta_1 - T_0) = \frac{(IR)^2}{8k/c} \tag{1}$$

where $c$ = electrical conductivity.

The law of Wiedemann and Franz states that at any temperature the ratio of the thermal conductivity $k$ of a body to its ohmic conductivity is approximately the same for all metals, and the value of the ratio is proportional to the absolute temperature $T_a$.

Equation 1 can then be written

$$(\theta_1 - T_0) = \frac{(IR)^2}{8yT_a} \tag{2}$$

where $y$ is the constant of proportionality.

As the absolute temperature increases, the ratio $k/c$ increases and $(\theta_1 - T_0)$ decreases.

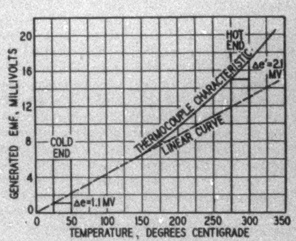


**Fig. 1. Variation of generated electromotive force with ambient temperature for a compensated thermocouple**

Millivolts available at 25 degrees centigrade ambient = 13.9

Millivolts available at 50 degrees centigrade ambient = 14.9

However, the resistance $r$ of the heater wire changes slightly with temperature. For the majority of materials $r$ increases with temperature and tends to offset the decrease in $(\theta_1 - T_0)$ caused by the increase in $k/c$. These 2 effects usually do not balance but tend to decrease $(\theta_1 - T_0)$, thereby acting to reduce the positive error previously discussed.

**W. N. Goodwin, Jr.:** J. H. Goss has referred to 2 possible sources of error in the compensated thermocouple ammeter, namely, that the thermal electromotive force generated is not a linear function of the temperature difference, and that the ratio of the electrical to the thermal resistivities is not constant for variations in temperature.

Although these statements are entirely correct, the errors introduced are only of the secondary order. For the temperature operating range of the heating conductor, these variations are calibrated directly into the instrument scale for one ambient temperature, which entirely eliminates such errors for the temperature at which the instrument is calibrated.

The final errors are the result of relatively small differences in the shapes of the thermocouple and resistivity curves caused by changes in ambient temperature.

J. H. Miller shows in a very interesting manner the methods actually used to correct for errors resulting from skin effect at very high frequencies.

## The Engineering Development of Electrochemistry and Electrometallurgy

**Discussion of a paper by Paul Bunet published in the December 1935 issue, pages 1320–31, and presented for oral discussion at the electrochemistry and electrometallurgy session of the winter convention, New York, N. Y., January 29, 1936.**

**C. Dantsizen** (General Electric Co., Schenectady, N. Y.): The opening paragraph of the author's excellent paper gives chemists something to think about. In the words of the translator, he states that "while one observer is impressed by the power of modern apparatus, its perfection, dependability, and the systematic organization of the plants, another observer considers rather the manufacturing processes, the chemical reactions which they bring into play, and according to the latter person changes have been rather slow during recent years."

In other words, the engineering development has been remarkable, while the chemical developments in electrochemistry in recent times have not been so remarkable either in number or commercial importance. This is a bitter pill for a chemist to swallow, particularly in this day and age when chemistry in other lines is making such rapid strides.

The reason for this state of affairs probably lies in the fact that the reactions involved in electrochemical and electrothermic processes are so simple that with the advent of tremendous electric power some thirty years ago, the field of applicable chemical reactions was relatively quickly exhausted by the enthusiastic investigators of that period. These pioneers left little to be done by their immediate followers.

The statement that the reactions involved in electrochemical and electrothermic processes are fundamentally simple is not made with the intent to detract from the achievements of these pioneers. It is always difficult to expose elementary ideas and we surely cannot blame them for doing such a thorough job in their generation.

There may be some question as to why these electrochemical and electrothermic reactions are elementary. The answer is that the nature of the processes involved make them so. With the theory of ionization firmly established as a good working hypothesis, as it was over 30 years ago, most of today's commercially successful electrolytic processes were quickly grasped by the bright young men of that early period.

Electrometallurgy and electrothermic processes involve chemical reactions at elevated temperatures. The more elevated the temperature of a reaction, the less complicated from a molecular standpoint are the reacting materials and the less complex are their reactions. None of us can write out even a small proportion of the reactions which take place in a living being at ordinary temperatures, but any first year chemist can make a good guess at the reaction for the formation of calcium carbide at high temperatures.

Does this mean that this field cannot expect any more help from the chemist and that the engineering will continue on its way unaided by chemists? Emphatically, no! During the past decade a brand new type of chemist has appeared in great numbers; men who specialize in physical chemistry; men who are well trained in the thermodynamics of chemistry. It is with these men our hope lies to give the electrochemical and electrothermic industries new processes, new methods, and improvements on existing processes and methods. These men have knowledge of thermodynamic principles little known thirty years ago and should give great help to the industry in question. Evidence at present indicates that the development of gaseous reactions at elevated temperatures will soon reach great commercial importance.

The study of such reactions has a special appeal to the physical chemist because their speed particularly in the presence of catalyzers is so great, and because they tend to follow so closely the laws of chemical equilibria. We have, for example, made hydrogen electrothermally from the hydrocarbon butane with the expenditure of only 30 kilowatt-hours per 1,000 cubic feet instead of 125 kilowatt-hours used in the electrolysis of alkaline water.

Our knowledge of chemical equilibria in oven atmospheres certainly is increasing and is finding wide application in heat treatment of steel and other metals.

Acetylene, which we obtain by the reaction of calcium carbide and water, has become the basis of huge chemical industries. As the author has illustrated so clearly, the cost of producing calcium carbide has been brought down very low by good engineering. Still it does not seem right that a substance which contains only carbon and hydrogen should have to be made by such a process. It seems as though it should be made commercially by direct synthesis or by the breakdown of higher hydrocarbons.

The foregoing are just illustrations of many processes which probably will reach commercial importance. It may be argued that many of such gas reactions are in the province of the combustion engineer as well as that of the electrical engineer. If this is so, they illustrate cases where the chemist has offered the electrical engineer reactions which, by the application of good engineering, can be held in the province of electrothermics.

If the author's first paragraph is accepted as true for the time being, it may be said that it does not seem probable that there is going to be a dearth of new electrochemical processes in the future.

**C. C. Levy** (Westinghouse Elec. and Mfg. Co., E. Pittsburgh, Pa.): The author of this paper has discussed, of necessity very briefly, the relative merits of the various alternating current to direct current conversion units which may be used in these industries. It might be interesting, therefore, to consider them somewhat more fully, and also in the light of accepted practice in this country.

The motor generator set and the synchronous converter have been used up to the present in practically all installations. The motor generator set is by far more flexible as far as voltage regulation is concerned, while the converter is superior in efficiency. The choice between the 2 installations depends to some extent on the relative importance given to these individual advantages.

A third conversion device, the mercury arc rectifier, is now available for this service, and it possesses certain advantages which have recently brought it into prominence. Although the author lists the large currents required in electrochemical work as a disadvantage, our experience in this country leads us to conclude that large currents do not present any difficulty for the mercury arc rectifier. For example, installations with units of 5,000 or 6,000 amperes capacity are not uncommon and larger capacities can be furnished. The low voltages in common use in these industries, however, do hinder the realization of the efficiency possibilities of the mercury arc rectifier.

At the usual voltage of 250 the efficiency of the motor-generator set and the mercury arc rectifier are of the same order. Above this voltage the mercury arc rectifier efficiency is better than that of the motor generator set, and at 500 volts it is slightly superior to that of the synchronous converter. In view of this, operating engineers are considering the use of 500 volts for many electrochemical processes, and some are actually using it at the present time. The difficulties from an insulation standpoint are slight in most cases. A more serious problem is the hazard to human life, where occasional operations are required on cells that are alive; another is that many installations use a multiple system for supplying the cell blocks, and are already organized on a 250 volt basis.

Both of these difficulties can be overcome in many instances. The first one may be avoided by connecting the neutral point of the cell string to ground, thereby reducing by 50 per cent the possible potential which an operator standing on ground and touching either the positive or negative terminal, might encounter. Insulation around the cells will, of course, remove the danger resulting from accidental contact with either positive or negative, and the physical separation of the ground and the positive and negative terminals preclude the possibility of contact between these points.

It is true that the leakage circuits to ground from the various cells, through circulating electrolyte, etc., are seldom equal in value or symmetrically disposed around the center of the cell string. As a result the actual electrical neutral may not correspond with the middle of the cell string. There is some question also as to whether a low resistance metallic connection to ground is necessary, in view of the fact that leakage paths through circulating liquid establish a ground of varying high resistance in any case.

It seems that the grounding of a point on the cell string can only be determined by an analysis of each individual case, since the operating conditions are not the same for various electrochemical processes.

The problem of dealing with installations already organized on a 250 volt basis in a measure takes care of itself, since at 250 volts there is a definite economic limit to the d-c capacity of a bus, beyond which segregation of power distributing busses becomes necessary in any case. There is, therefore, no reason to prevent a large plant, reaching its 250 volt capacity, from installing additional power at 500 volts to form the nucleus of a 500 volt distribution which will have twice the energy available for the same amount of copper and will operate at higher efficiency.

Interchangeability of units still may be provided in emergency by arranging the rectifier transformer for 250 volt operation getting in this way approximately half the capacity of the rectifier in case an interconnection with the 250 volt system becomes necessary.

Future improvements in mercury arc rectifiers for this service are to be expected. A recently developed device, the igniter type of mercury arc rectifier, will show efficiency comparable to that of the synchronous converter at 250 volts, because of its inherently lower arc voltage drop. With this additional conversion device, the needs of the industry are well supplied.

# Power and Energy, Positive and Negative

**Discussion and authors' closure of a paper by L. A. Doggett and H. I. Tarpley published in the November 1935 issue, pages 1204–9, and presented for oral discussion at the instruments and measurements session of the winter convention, New York, N. Y., January 28, 1936.**

**A. E. Knowlton** (*Electrical World*, New York, N. Y.): The authors have been kind enough to refer to my contributions in company with those of W. H. Pratt and Vladimir Karapetoff. It might add to an appreciation of the significance of the present paper to show the practical value of the power ratio in circumventing the mysteries of power factor to those lay individuals who encounter a power factor clause in their power contracts. They lack the time or acumen to penetrate the domains of vectors, sinusoids, and harmonic components. For them a more convincing concept would be desirable, especially if it carried more actuality than the suppositious reactive kilovolt-ampere component which is the basis of most power factor metering.

Thus it should not be difficult to educate power users to the progressive shift of the energy flow from all positive to more and more negative as reactive loads enter to store energy and disjoint the simultaneity of current and voltage alternations. Energy which is reciprocating between load and source to balance the inequality of instantaneous generation and consumption is a tax on all facilities, both line and terminal. That all physical reality is lacking in the case of the conventional reactive power may be seen from figure 1 of this discussion. Contrary to the common concept, reactive power does not flow back and forth in the line. The only actual reciprocating transfer is the energy represented by the negative loop of the displaced power wave and its counterpart in the positive loop. Part of what is called reactive power never leaves the inductive locale. It accumulates there and then shifts to augment the useful application as torque or heat. It is only the negative loop which is involved in actual energy reciprocations. The quantity $D$ identical with $C$ does not return over the line to the generator. It is a delayed interaction of energy temporarily stored in the reactive element of the receiver.

In addition to the practical lay appeal of the power ratio there is the further fact that power ratio is much closer in proportionality to the excess capacity factor $(1 - \cos \theta)$ occasioned by low power factor than is the reactive component usually measured. This can be seen from figure 2 of this discussion.

However, it must be admitted that what may be gained in persuasiveness of the power ratio concept with the nontechnical power purchaser is wholly lost in academic simplicity. Once the student has mastered elementary vectors and sinusoids he acquires a grasp of power factor and cos $\theta$. Imagine, if you can, his bewilderment if he be asked to view the ineptitude of energy consuming systems through the medium of the formidable expression

$$[(\pi - \phi) \cos \phi + \sin \phi]/(\phi \cos \phi - \sin \phi)$$

for the power ratio instead of the simple factor cos $\theta$ now employed.

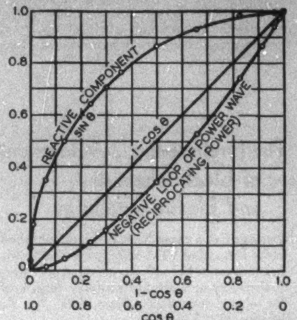


**Fig. 2. Curves showing that reciprocating power is a better index of excess capacity than is the reactive component**

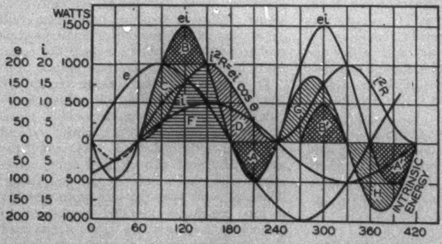


**Fig. 1. Sinusoidal waves showing that only a part of the reactive component reciprocates as energy between alternator and reactive receiver**

A sinusoidal voltage e sustains a sinusoidal current *i* through a series circuit of inductive reactance and noninductive resistance, so proportioned that *i* lags e by 60 degrees. The voltage, the current, and the instantaneous energy flow at the receiver terminals. Within the receiver energy is stored in and recovered from the magnetic region which constitutes the inductance, and energy is converted to heat, light, and mechanical work. During the period from 60 degrees to 150 degrees the receiver is taking energy from the line, and the energy is not being converted to heat, light, and mechanical energy as fast as it is delivered to the receiver. During this interval $e \times i$ exceeds $i^2R$ and energy is being stored in the magnetic field. This is represented by the sum of the areas *B* and *C*. After $e \times i$ decreases to equality with $i^2R$ at 150 degrees, the energy being converted in the receiver is sustained by a transfer of energy *D* from the quantity stored in the magnetic field. This quantity *D*, identical with *C*, does not return over the line to the generator. After the initial transfer of this energy from the generator to set up the magnetic field, it remains within the confines of the receiver

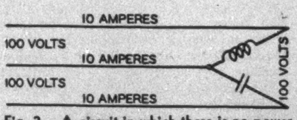


**Fig. 3. A circuit in which there is no power and no reactive component, yet power factor is unity**

Presumably we shall have to continue to tolerate the vagaries of power factor in erudite circles because they resist simplification and clarification but there is some reason for grasping for a substitute in commercial practice. That is especially true with the growth of furnace and welding loads that promote distortion and unbalance. The authors have contributed something significant to the case of distortion but apparently they leave polyphase unbalance practically unanswered. In the matter of distortion, however, it is not clear that figures 8 and 10 of the paper should be construed as condemning the rectification method of ascertaining the power loop ratio. If the reference curve in each case were modified to reflect the degree to which true power factor is affected by harmonics, it is possible that the discrepancies between curve and experimental data would vanish.

As for the unbalance and lack of symmetry, I would ask whether the authors have applied their method or analysis to the extreme situation presented in figure 3 of this discussion. Here the power is zero, the reactive volt-amperes are zero, the total volt-amperes 1,730, and the power factor would be unity. I would ask whether the authors have explored this ideally extreme case and what their technique would show as to power ratio and also as to power factor interpreted from power ratio. Such a circuit is not likely to be encountered in practice but it does help to disclose weaknesses that might otherwise remain concealed in a practical situation.

**W. C. Wagner** (Philadelphia Electric Co., Philadelphia, Pa.): The authors have demonstrated that positive and negative energy and power may be measured approximately, and that a power ratio determined from the relation of positive to negative energy or power is measurable, definable, and readily interpreted for single phase and balanced 3 phase conditions, regardless of wave shape.

Considerable credit is due the authors and also A. E. Knowlton and W. H. Pratt for their work in attempting to provide a means of interpreting circuit conditions in a more scientific way than by use of the term power factor.

In practical commercial measurements consideration must be given not only to the accuracy for a measurement, which is of relatively minor importance in determining charges made for electric service, but also to continued reliability, cost of maintenance of the measuring equipment, and the economic value of a possible improvement in the accuracy of the determination.

There is no question of the accuracy of the energy measurement itself, and this and the maximum demand represent the prime factors on which charges are made for electric service. In the practice of many utilities an adjustment for power factor is made only to the maximum demand, and experience has shown that there is little variation in power factor values for specific customer loads under actual operating conditions approaching maximum loads (see "Compensating Metering in Theory and Practice," G. B. Schleicher, A.I.E.E. TRANS., v. 52, Sept.-Dec. 1933, p. 816–23). Experience has indicated also that in most cases the continuous measurement of power factor is not justified by the economic value of the possible minor variations which would be found, as compared with a test made at intervals under conditions approaching the maximum demand (see "Operating Aspects of Reactive Power," by J. A. Johnson, ELEC. ENGG., v. 52, April 1933, p. 262–8). The same conclusions very properly apply to a determination of power ratio as proposed by the authors.

The improved accuracy of the proposed method is open to question. While its chief advantage is the evaluation of a nonsinusoidal wave shape, it should be noted that the copper oxide rectifier itself causes changes in wave shape ("Copper Oxide Rectifiers in Ammeters and Voltmeters" by Edward Hughes, *Journal* of the Institution of Electrical Engineers, 1934, p. 462). While this effect may be reduced greatly by connecting a low resistance shunt across the current transformer, it is possible that a similar effect would be apparent in the rectified current of the type 80 tube. The effective impedance of the latter will also change with variations in the supply voltage because of their effect on the voltage applied to the filament. The effect of the relatively large burden on the current transformer should be considered, and the d-c meter itself, with its commutator and heavy moving element, has not reached either the reliability or the high degree of accuracy of the a-c induction watt-hour meter which may be used for measuring energy and reactive kilovolt-amperes.

While small generators sometimes have nonsinusoidal voltage waves, for practical purposes this does not apply to the supplies of the large interconnected utility systems of today; hence, the proposed method may be considered primarily in the light of possible distortion of current wave forms, which may be produced by the exciting current of transformers, static condensers, arc welders, etc. In practice, distortion produced by such means is generally superimposed upon larger currents of sinusoidal characteristics, and the distorting effect on the resultant current becomes negligible for purposes of practical measurement. This is particularly true under maximum loads for which power factor determination, or an equivalent measurement, is of value for billing purposes.

For the scientific investigation of circuits in which harmonics are present, a method such as that proposed will undoubtedly be of value. From a commercial standpoint, power factor supplies a distinct need (see "Reactive Power and Power Factor," W. V. Lyon, A.I.E.E. TRANS., v. 52, Sept.-Dec. 1933, p. 763–70), in that it serves a useful purpose for specifications of power rates, and its measurement from the relation of reactive kilovolt-amperes to kilowatts is sufficiently simple for use in practical commercial measurements.

**W. H. Pratt** (General Electric Co., W. Lynn, Mass.): This paper deals with an interesting departure from the ordinary way of evaluating the flow of energy in an a-c circuit. In place of quantities which have only a nominal existence in circuits other than those in which the flow of energy is sinusoidal, the quantities here discussed have a tangible existence.

In the polyphase circuit there seems to be an arbitrariness in their selection; that is, into a balanced polyphase circuit as a whole there may be no negative flow of energy but there is still an alternating flow between its component parts.

The value of the paper appears to be that it affords an opportunity to discuss the value of a particular conception of measurement in its relation to practical problems. As was suggested by the writer (see "Notes on the Measurement of Reactive Volt-Amperes," W. H. Pratt, A.I.E.E. TRANS., v. 52, Sept.-Dec. 1933, p. 771–9) there may be a real use for this conception in rate making, but it is for the rate makers to say if this is so. The reason for the suggestion is the moderate rate at which the ratio of positive to negative energy undergoes change with the departure from unity power factor, in contrast to the very rapid increase of reactive volt-amperes.

It does not seem, in spite of the possibility of unequivocal numerical statement, that this group of conceptions would find much place in design problems. It is also true that the considerable array of so-called powers apparent, reactive, distortion, etc., may correlate with numerical identity conditions that have little in common when the wave forms are distorted. The authors give no clue to the procedure that should be adopted to effect an improvement in a particular situation. In the writer's paper just mentioned there was pointed out a means of measurement of the values of positive and negative flow of energy resulting in much more accurate determination than is obtainable by the direct measurements of Doggett and Tarpley.

**L. A. Doggett** and **H. I. Tarpley**: It is a source of a good deal of satisfaction to the authors to find so many workers in this field independently arriving at much the same conclusions as our own. We therefore agree with much of the discussion that has been presented.

In connection with W. C. Wagner's discussion, it should be pointed out that the errors to which he has referred are largely eliminated in the measurement of power ratio, where a particular percentage error in the denominator is canceled by approximately the same percentage error in the numerator. Evidence of this is shown by figure 7 of the paper.

It should be noted that in the case of a small industrial load with a 100 kva bank of transformers utilizing static capacitor power factor correction, the present day measurements of power factor are little better than a guess because of deviation from sinusoidal conditions. Presumably upon this guess is based the customer's improved rate following the installation of static capacitors.

We have not been accustomed to students becoming bewildered by the expression for the ratio of the 2 wattmeter readings on 3 phase power measurements,

$$\frac{W_2}{W_1} = \frac{\cos(30+\theta)}{\cos(30-\theta)} \text{ or } \tan\theta = \sqrt{3}\,\frac{W_1 - W_2}{W_1 + W_2};$$

therefore, we anticipate no difficulty from the trigonometrical expression for power ratio, presented in the paper. In the very interesting case of a polyphase unbalance, the power ratio was quoted for 8 cases. These ratios give an indication of what is taking place at the boundary where the measurements are made. That the power ratio is descriptive of the over-all behavior of a polyphase unbalanced load is amply substantiated by the data of table I. In this case 15 different circuits, all considerably unbalanced, some circuits composed of units of resistance and inductance, others composed of units of resistance, inductance, and capacity, were tested for power ratio, first with clockwise and then with counterclockwise phase rotation. It is common

Table I

| Load | Power Ratio | |
|---|---|---|
| | Clockwise | Counterclockwise |
| R, L, C | 1.5 | 1.66 |
| R, L, C | 1.42 | 1.48 |
| R, L, C | 1.62 | 1.86 |
| R, L | 4.57 | 4.42 |
| R, L | 5.48 | 5.25 |
| R, L | 4.78 | 4.66 |
| R, L | 5.44 | 5.45 |
| R, L | 1.85 | 1.86 |
| R, L | 2.6 | 2.53 |
| R, L | 3.26 | 3.19 |
| R, L | 3.28 | 3.32 |
| R, L | 3.73 | 3.68 |
| R, L | 1.88 | 1.90 |
| R, L | 2.02 | 1.88 |
| R, L | 3.79 | 4.02 |

knowledge that a change of phase rotation in the supply of an unbalanced 3 phase load produces a completely new set of currents and phase relations, although the load itself is left unchanged. The power supply and the power ratio remain the same for either direction of phase rotation.

In the case referred to by A. E. Knowlton as figure 3 of his discussion, one wattmeter would have a positive power reading of 318 watts, the other a negative power reading of 318 watts, giving a net power reading of 0. The power ratio is, therefore, $\frac{318 + 318}{318 + 318} = 1$ In simple language the interpretation is that the net power is zero, since there is an equal amount of positive and negative power. In answer to the question as to what is the power factor of this circuit our answer is that we do not know, and nobody here or abroad knows, because after a 50 year struggle power factor still remains undefined.

## Power Company Service to Arc Furnaces

**Discussion of a paper by L. W. Clark published in the November 1935 issue, pages 1173–8, and presented for oral discussion at the electrochemistry and electrometallurgy session of the winter convention, New York, N. Y., January 29, 1936.**

**H. O. Stephens** (General Electric Co., Pittsfield, Mass.): A large part of L. W. Clark's paper is devoted to lamp flicker difficulties occasioned by fluctuating furnace loads during the starting period, particularly when furnaces are used for melting cold scrap. Several suggestions are offered for improving this condition. It is believed that the following corrective measure will provide a satisfactory solution for some installations.

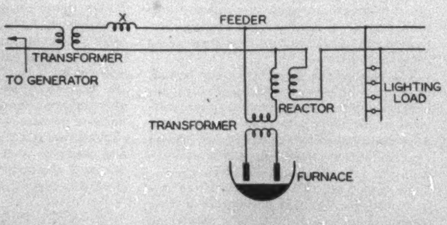


**Fig. 1. A method of reducing lamp flicker on a feeder supplying a single phase arc furnace**

Figure 1 shows a feeder delivering power to a single phase arc furnace and miscellaneous lighting load. Let *X* represent the reactance of the feeder including the feeder transformer reactance. Most of the smaller arc furnaces are provided with series reactors. If the series reactor is provided with a separate winding connected in series with the feeder and having a mutual inductance between the 2 windings corresponding to the reactance *X* in the feeder, then the feeder voltage will be boosted an amount corresponding to the reactive drop due to the furnace load in the feeder.

Although figure 1 shows the connections for a single phase furnace, the scheme would work out equally well with a 3 phase furnace.

**C. L. Dudley** (Public Service Electric and Gas Co., Newark, N. J.): If the use of electric energy for direct applications in industry is to improve the practice of the user, equipment manufacturers and power supply engineers must all appreciate the problems and viewpoints of the others and co-operate in obtaining a best engineering solution. At this session a real step has been made in the presentation of some of these mutual electrical problems. Sound fundamental engineering has been applied in the case of certain very vexing ones.

With the power supply engineer the type of load resulting from the use of induction heating equipment or the resistor furnace meets a long standing criticism. They are steady loads of high power factor. It has long been one of the problems of the distribution engineer to supply service to the single phase arc furnace loads which are to be encountered among the steel jobbing foundries. They are not large loads as a rule; hence, they can be served economically only from the low voltage distribution systems. The consequent voltage disturbances create a very real barrier to the increased use of such equipment. If the resistor furnace can be made to give the superior qualities of electric iron or steel at an efficiency comparable with that of the electric arc, then a great step forward has been made.

The author clearly outlines the major supply problems of arc furnace loads. The oscillograms should be particularly helpful to all engineers who are required to pass on the practicability of serving this type of load. The use of reactor starting should be given much greater consideration than it has in the past. Its cost is a very small addition to that of the entire furnace installation and the reduced inrush current, as well as the increased arc stability, may well mean the difference between the ability to serve and the failure to serve.

Another point indirectly raised by the author could well be considered by prospective users of electric furnaces and by the power salesmen of utility companies. It relates to the matter of location with respect to the permissible voltage disturbances to other customers. Where a prospective furnace user is entering a new locality or moving from one establishment to another, it would be very desirable to consider the availability of adequate power supply at minimum cost along with the other factors usually considered.

Differences in design and operation of transmission systems will affect the matter of placing small transformer installations for furnace supply on these lines. They may complicate relaying and create grave hazards to service continuity to other customers.

The use of maps to indicate areas in which furnace load can be accepted is probably somewhat limited. They may be applied readily to some systems and not so readily to others. It is difficult to understand how they could be put into the hands of any but competent engineers of the power company for interpretation, and it is suspected that this is the use to which they are put by the Detroit Edison Company.

**W. A. Lindberg** (Commonwealth Edison Co., Chicago, Ill.): The distribution and density of industrial load in the Detroit area is apparently such that independent power circuits are justified. In most cities, of course, this is not the case. Where furnaces of the order of from 100 to 500 kva are being considered, an attempt should be made to provide service from the general distribution system, because usually the cost of extending and furnishing adequate terminal facilities on the higher voltage lines is relatively high.

About 50 per cent of the distribution systems in the United States are 3-phase 4-wire. Providing service to a single phase furnace from such a system brings up the problem of the best kind of service connection to use. Service may be given from phase to phase, either direct primary or low tension through a special transformer; from phase to neutral, either direct primary or low tension through a standard transformer; low tension from one phase of a star-delta bank; through the so-called Z connection, which is a star primary with the neutral closed, and secondary similar to delta, except that the delta is not closed at one point, and secondary of one transformer is reversed.

Table I shows relative values of significant factors to be considered in studying service to furnaces from 3-phase 4-wire systems. Where affected by variable conditions, the values shown are based on a distribution circuit of $1^1/_2$ miles of number 2/0 overhead wire, equipped with 200 ampere regulators. The voltage fluctuations are calculated on the basis of a power factor of 0.40 for the corresponding load change. Figures for voltage fluctuations with 3 phase furnaces are not shown because a study of the paper indicates that this comparison is not susceptible to mathematical treatment.

Where conditions are such that voltage regulation is a problem in providing service to a single phase furnace, not only must the various schemes be compared on the basis of highest fluctuation for each connection but also the relative fluctuation on the other phases for each connection. Lamp flicker allowed should be below that which is regarded as objectionable but may be above a value which is just visible. From the standpoint of voltage regulation, connection number 2 is the least desirable for any combination of load and circuit characteristics. The choice among numbers 1, 3, and 4 will depend on individual circumstances.

The increase in circuit loading for each type of connection should be considered not only on the basis of total kilovolt-amperes, but also with regard to the unbalance between phases. Current in the neutral conductor usually is not significant when considering circuit capacity. The capacity necessary for connections number 2 and number 5 is the same, but obviously number 5 is better because in number 2 much of the capacity of *B* and *C* phases would be useless unless other single phase furnaces or similar loads were available. No generalization can be made of the relative amount of circuit capacity to be reserved for each connection on account of probable difference in power factor of furnaces and other loads on the circuit, and because of the variation in the phase angles of the currents due to the scheme of transformation in connections numbers 1, 3, and 4. Unless load is available for balancing in number 2, scheme number 1 probably is best from the point of view of circuit capacity for single phase loads.

Connections number 3 and number 4 require extra transformer capacity. Number 3, however, may not cause a higher transformer investment because it is possible to supply furnace and power load from the same bank.

In most cases, 3 phase service to a 3 phase furnace is the best situation. Further test data and explanations on the subject of relative fluctuations resulting from single phase and 3 phase furnaces would be useful. Of the single phase services, number 2 can be ruled out on the basis of poor voltage regulation and number 4 on account of the high circuit and transformer capacity required. The choice between number 1 and number 3 will depend on individual circumstances.

It is probably true that, until the publication of this paper, many engineers received their impressions of characteristics of arc furnaces by listening to the staccato roar and by observing the gyrations of indicating instruments. Having in mind the precautions taken in fixing starting currents of motors to protect quality of service, it was only natural to be cautious in connecting furnaces whose starting period is a matter of minutes rather than seconds. The information given in L. W. Clark's paper will be extremely useful to distribution engineers.

**P. G. Sturtevant** (Erie County Electric Co., Erie, Pa.): In commenting on L. W. Clark's paper a brief description of the set-up of the company with which the writer is connected may be interesting as far as it concerns the electric arc furnaces on its lines.

It is a relatively small company. The peak load is about 12,000 kw, and the normal load during the day is about 8,000 kw. Normally one turbine of 12,500 kw capacity is operated. There are no continuous interconnections with other companies, although there is an emergency connection with the local plant of another utility company available, in case serious trouble with equipment or supply develops in either company.

There are 2 arc furnaces located in a steel foundry. One has a rated capacity of $1^1/_2$ tons, and the other a 3 ton rated capacity. They are 3 phase furnaces, with transformer ratings of 750 kva and 2,000 kva, respectively. The central station generates at 14,000 volts, and this voltage is delivered via a substation directly to the furnace transformers, a total distance of about $1^1/_4$ miles. This substation is served by 2 3-conductor cables of 300,000 circular mils each. During the first 15 minutes of operation the disturbance of the system voltage is very marked as a rule.

Several expedients such as running 2 turbines during the time the furnace is in operation, or connecting the emergency line with the other electric supply company in Erie, have been tried to reduce this fluctuation. Both of these were considered too costly to be justified by the small improvement made. Arrangement was finally made with the customer's management to change the operating hours so that they would start at midnight. This arrangement has done a great deal to relieve complaints, although some customers, such as X ray operators, still are affected.

Table I—Relative Values of Factors to Be Considered in Studying Service to Furnaces From 4-Wire 3-Phase Systems

| | | | Voltage Fluctuation, Per Cent Primary Phase to Neutral | | | Primary Amperes, Per Cent Normal Operation[I] | | | | Total Primary Phase, Amperes | Total Distribution Transformer Capacity, Per Cent |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Connection Number | Connection | Service | *A* Phase | *B* Phase | *C* Phase | *A* Phase | *B* Phase | *C* Phase | Neutral | | |
| 1 | Single phase *A* phase to *B* phase | Single phase | 100 | 94 | 0 | 100<br>$\theta - 30^\circ$ | 100<br>$\theta + 30^\circ$ | 0 | 0 | 200 | 100 |
| 2 | Single phase *A* phase to neutral | Single phase | 328 | 44 | 92 | 173<br>$\theta$ | 0 | 0 | 173 | 173 | 100 |
| 3 | Star-delta | Single phase | 129 | 29 | 36 | 115<br>$\theta$ | 58<br>$60^\circ + \theta$ | 58<br>$60^\circ - \theta$<br>Leading | 0 | 230 | 133 |
| 4 | Z connection[II] | Single phase | 29 | 88 | 99 | 87<br>$\theta$ | 87<br>$60^\circ + \theta$ | 87<br>$60^\circ - \theta$<br>Leading | 87 | 260 | 150 |
| 5 | 3 phase | 3 phase | | | | 58<br>$\theta$ | 58<br>$\theta$ | 58<br>$\theta$ | 0 | 173 | 100 |

I. Phase angle with respect to phase-to-neutral voltage is shown. $\theta$ is the power factor angle of furnace load.

II. The *Z* connection consists of a star primary and secondary coils so connected in series that the output voltage is twice the voltage per coil.

In going over the author's 4 considerations affecting and governing procedure to be followed in serving the electric furnace load, it is believed that number 3 is by far the most important.

It is the writer's experience that the care with which the furnace is charged has a great deal to do with magnitude of the voltage variations, for when large chunks of scrap are irregularly piled on the top of the furnace charge, and until these large pieces are pretty nearly melted, extreme surges of current result. It has been suspected at times that the operator of the furnace has neglected to start his furnace on the higher impedance tap of the transformer, in the belief that he could speed the melting operation by starting on the intermediate tap.

An electric furnace expert was employed to observe the operation of the electric furnace that was causing the most trouble, and, after watching the operation for several weeks, his conclusions were that good or bad furnace operation rests largely with the operator, and that there is no positive way for the electric company to control this operation.

The writer's efforts have therefore been directed toward minimizing the bad effects caused by the furnace rather than toward trying to prevent such voltage fluctuations. To this end recently a time delay relay was installed on one of the 3 phase induction feeder regulators. This relay was installed on the boost circuit of the contact voltmeter and has been set to give a 4-second delay in the motor operation.

The voltage fluctuations at the substations were aggravated by the hunting of the feeder regulators while the furnaces were in operation. Immediately upon installation of the time delay relay there was a complete cessation of regulator hunting. The improvement was so marked that 4 more of these relays were ordered and are now being installed. Undoubtedly all of the regulators will finally be so equipped.

**C. A. Powel** (Westinghouse Elec. and Mfg Co., E. Pittsburgh, Pa.): The Detroit Edison Company is to be commended on attempting to set up a classification of voltage flicker and it will be interesting to observe how the limits selected will stand the test of time.

A method of correcting flicker trouble not mentioned in L. W. Clark's paper and which should prove applicable in many cases is the use of a series capacitor. It is instantaneous in operation and will provide effective compensation for line drop where the circuit is largely reactive and this comprises the majority of circuits. The hermetically sealed, fireproof capacitor has reached a stage of development at which it is quite reliable for such service, and a simple scheme of control protects it against overvoltage due to short circuit in the feeder beyond the capacitor and also against a faulty capacitor unit. The scheme of control is such that the series capacitor is self-restoring for overcurrent and feeder short circuits after the trouble has been removed, but remains permanently out of service in the case of a faulty unit.

The series capacitor does not compensate for variations in bus voltage caused by load conditions external to the feeder under consideration. If, therefore, it is used to correct for voltage flicker, it must be supplemented by other regulating means to take care of bus voltage variations.

**J. E. Sheehan** (Houston Lighting and Power Co., Houston, Texas): An electric steel casting company, a customer of the company with which the writer is associated, has installed an electric furnace with a normal rating of 1,250 kva. This furnace is located on one of the 12 kv power circuits feeding from the 12 kv bus of a substation, which in turn is fed from the power plant through 33 kv lines and transformer banks.

The contract with the steel company involves off-peak service, the furnace being put into use about 10 p. m. and used until the early morning hours. There is not a great amount of lighting service on the 12 kv circuit from which the furnace is fed; however, the disturbance is reflected back through the bus to other 12 kilovolt circuits and the 12 kv network system. At times the disturbance is very pronounced. Complaints have been received from broadcasting stations, and in some instances, operators of picture machines.

The trouble appears to be more in the method of operating the furnace than in any inherent defects in the design. From time to time the company communicates with the operators of the furnace and for a short time thereafter the disturbances are greatly reduced; however, they soon return to the habit of loading the furnace to the limit upon starting.

Various ways and means of isolating the disturbance have been considered: (1) Installing a separate bank of 33 kilovolt stepdown transformers on the customer's premises in order to feed the furnace directly from one of the 33 kilovolt tie circuits. (2) Installing a separate bank of transformers at the substation to feed the 12 kilovolt circuit directly and remove from the circuit all loads affected by the disturbances involved only. (3) Installing a current-limiting reactor on the circuit feeding the furnace, to be located at the substation. This scheme would tend to eliminate disturbances on the system as a whole, but would greatly increase the disturbances to other loads fed from the circuit. (4) Installing a current-limiting reactor in the vicinity of the furnace.

The company hesitates to install current-limiting reactors, for their use would tend to affect the operation of the furnace. There is also some hesitation about isolating this furnace, since the expense involved would be considerable, and would set up a precedent which might force the company to follow in serving other furnaces; therefore, an attempt has been made to deal with the steel casting company and the manufacturer to arrive at a method of operation and a type of control equipment which will solve the problem. To date no great amount of co-operation has been received from the manufacturer, but some results have been obtained by working with the furnace operators.

**C. P. Yoder** (Buffalo, Niagara and Eastern Power Corp., Buffalo, N. Y.): L. W. Clark's analysis, based on 4 considerations having to do with the electrical characteristics of arc furnaces, determines the type of service necessary to meet these conditions. This is extremely valuable data for the guidance of utility men interested in servicing such loads.

While an investigation of line disturbances is important from the standpoint of utility investment to insure satisfactory service, the writer would like to suggest a fifth consideration of equal importance as justification for such investment, that is, a careful study of the annual power consumption anticipated from the prospective load. The author, in the introductory paragraph of his paper, calls attention to the anticipated high load factor and revenue producing possibilities of electric melting furnaces. This unqualified statement appears to overlook the fact that melting furnaces, like all other power consuming devices, are susceptible to a great variety of uses and resulting revenue possibilities.

Electric melting furnaces used by industries organized on a mass production basis or by some of the alloy steel companies may result in load factors comparable to the usual run of industrial power loads; on the contrary there are a great many installations where intermittent use results in very low power consumption. Obviously that load which develops the highest load factor is the most desirable and should merit the most consideration.

I have assembled some figures from a number of furnace installations to illustrate the wide range of annual load factors that are encountered in practice. Table II also shows the year-to-year variations for individual installations. While these figures are from but a few of the several hundred arc furnaces installed in this country, they suggest the importance of a careful analysis of the anticipated kilowatthour consumption from prospective furnace installations.

**H. P. St. Clair** (American Gas and Electric Company, New York, N. Y.): Many power companies have encountered an electric furnace supply problem at some time or other, but few have had such a broad range of experience as the Detroit Edison Company has had, covering practically all sizes and types. Consequently,

**Table II—Annual Load Factors of Electric Arc Melting Furnace Loads**

| Company Designation | Approx. Demand, Kw | 1927 | 1928 | 1929 | 1930 | 1931 | 1932 | 1933 | 1934 | 1935 | Remarks |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 1,500 | | 21.0 | 24.2 | | | | 5.75 | 8.16 | 15.9 | Steel foundry—furnace only |
| 2 | 1,800 | | | | | | | 1.48 | 4.87 | 4.3 | Steel and iron foundry—furnace only |
| 3 | 3,600 | | 18.4 | 22.4 | | | | 5.42 | 5.92 | 8.08 | Steel foundry—furnace only |
| 4 | 2,200 | | | | | | | 7.7 | 8.3 | 8.5 | Steel foundry—furnace only |
| 5 | 800 | | 7.35 | 7.8 | 5.9 | 3.13 | 2.77 | 3.26 | 3.68 | 4.44 | Steel foundry—furnace and power load |
| 6 | 5,500 | | | | | | | | 15.2 | 22.4 | Alloy steel ingots—furnace only |
| 7 | | | | | | | | | | 12.0 | Small cold melting foundry—furnace and power load |
| 8 | | | | | | | | | | 19.0 | Small cold melting foundry—furnace and power load |
| 9 | | | | | | | | | | 22.0 | Small cold melting foundry—furnace and power load |
| 10 | | | | | | | | | | 30.0 | Large production foundry, duplexing—furnace and power load |
| 11 | | | | | | | | | | 45.0 | Large production foundry, duplexing—furnace and power load |
| 12 | | | | | | | 6.62 | 11.9 | 15.7 | 18.5 | High grade alloy steel castings—not known if power load is included |
| 13 | | | | | | | 10.4 | 14.45 | 19.4 | 12.5 | High grade alloy steel castings—not known if power load is included |
| 14 | 300 | 14.2 | 17.0 | 20.2 | 21.0 | 14.4 | 4.3 | 7.2 | 14.7 | 14.3 | Furnaces only |
| 15 | 300 | | 6.9 | 11.2 | 9.7 | 7.4 | 4.1 | 8.7 | 9.8 | 7.4 | Furnaces only |
| 16 | 600 | 16.0 | 16.2 | 14.7 | 12.7 | 6.5 | 3.8 | 11.3 | 16.8 | 13.0 | Furnaces only |
| 17 | 1,000 | 15.5 | 19.5 | | | | | | | | Furnaces only |
| 18 | 3,500 | 14.9 | 28.0 | | | | | | | | Furnaces only |
| 19 | 1,500 | 20.1 | 24.0 | 29.4 | | | | | | | Furnaces only |
| 20 | 1,000 | 3.7 | 11.4 | 11.4 | | | | | | | Furnaces only |
| 21 | 1,800 | 5.2 | 6.9 | | | | | | | | Furnaces only |
| 22 | 600 | 14.0 | 15.8 | 18.1 | | | | | | | Furnaces only |
| 23 | 800 | 28.0 | 13.3 | 18.5 | | | | | | | Furnaces only |
| 24 | 2,700 | 22.0 | 27.3 | 33.0 | | | | | | | Furnaces only |
| 25 | 1,000 | 27.7 | 32.4 | | | | | | | | Furnaces only |
| 26 | 1,400 | | | | | | | 17.55 | 22.1 | 22.5 | Furnaces only |
| 27 | 1,100 | | | | | | | 14.9 | 17.5 | 22.4 | Furnaces only |

Load factors are calculated from highest monthly demands and expressed in per cent.

the industry is particularly indebted to L. W. Clark for presenting a picture of this experience in such a clear and comprehensive manner. The examples and data which he has presented in this paper will undoubtedly prove of great value to other companies who may now and then be confronted with an isolated problem.

Out of a number of electric furnace installations on the system of the company with which the writer is connected, there is one in particular which has given rise to some voltage flicker complaints. This furnace is supplied in the manner shown in figure 2 of this discussion. At the time this furnace was installed there was not enough information about its characteristic load swings to attempt an exact determination of resulting voltage fluctuations, but it was felt that the installation provided should be ample to take care of it satisfactorily. As a matter of fact, the effect on the distribution system has not been objectionable except for a few isolated periods when particularly heavy loads were being put on the furnace.

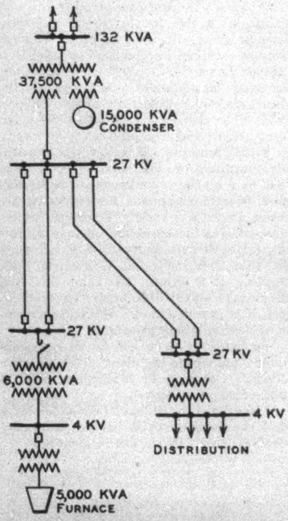


**Fig. 2. An electric furnace installation characterized by high arc stability but objectionable voltage flicker**

Referring again to figure 2, the 15,000 kva synchronous condenser, operating on the 132 kv transformer bank, undoubtedly provides some stabilizing effect on the voltage, but of course this effect is limited to the inherent voltage-kilovolt-ampere characteristic of the condenser since these fluctuations are entirely too sudden for any regulator or excitation system to follow.

It might be pointed out that the use of series reactance to cut down voltage fluctuations during the starting period also has the advantage of giving a more stable arc during this period when there is a tendency for the arc to be rather unstable and occasionally to go out. With this reactance in the circuit, even if the voltage is increased somewhat to maintain a fairly high value of current, the fluctuations might still be less because of the resulting increase in arc stability.

**C. M. Weinheimer** (Detroit Electric Furnace Co., Detroit, Mich.): L. W. Clark's paper is a most helpful analysis of a load which in this country probably ranges between 300,000 and 500,000 kw. When the possible annual return from this business is considered it is surprising that so few measurements have been made to determine its true characteristics. In 18 years of installing indirect arc rocking furnaces, the problem of arc furnace loads, and the cost of serving them necessarily has been dealt with. During this period approximately 500 units of this type have been installed in the United States and Canada and not one has been discontinued because of objectionable load characteristics. No special starting devices were used in any of these installations. Clark's data on the characteristics of indirect arc rocking furnaces with starting reactors is the result of a co-operative study made by the Detroit Edison Company and the company with which the writer is associated on a commercial installation to determine what could be done along these lines.

With a great many utilities, a very human and expectable situation develops when an arc furnace load is first discussed. They anticipate trouble resulting from a pyramid of conditions, such as the starting of cold furnaces at an hour in the day when all the circuits are heavily loaded, that the circuits serving it will likewise serve sensitive customers where voltage flicker will be objectionable, and that such variation will be noticed and cause complaint. The result is much discussion about the desirability of the furnace load, the cost of serving it, the revenue to be expected, and the use of starting devices. Such situations are normal, honest, and reasonable. Actually, however, these theoretical conditions fail to appear, although they might, and the usual outcome is the acceptance of the load without restrictions.

The author's measurements and analysis of furnace loads under practical operating conditions have given utility engineers a true picture of the starting characteristics of electric arc furnaces. With this definite knowledge available a utility should be able to estimate quickly the cost of serving an installation which will provide a return of 20 dollars to 40 dollars per kw-year. There are probably more than 1,000 electric arc melting furnaces in the United States, ranging in size from 36 kva to 10,000 kva.

The foundry industry is highly competitive. The utility, the foundry industry, and the furnace manufacturer all realize that electrical energy is a refined product, thus carrying an extra cost burden. Electric melting need not always compete with fuel but can supplement it with benefits to the ultimate consumer. Another plan tending to reduce the cost of electric melting is the operation of the furnaces only during the off-peak hours. The foundry must weigh this saving against the added cost of night operation, but the utility's generating and distribution system certainly will show an off-peak idle capacity far in excess of any conceivable electrification in the foundry industry.

The advent of metals made to rigid specifications, especially in the ferrous field, has created a demand for electric melting which should be encouraged. Furnace manufacturers have a continual obligation in simplifying and improving the operation of their products, thus making repetitive results easier to achieve. The control available with electric melting provides a method of producing metals which meet these rigid specifications.

There is a foundry business which has been served in the past with electrical energy for melting, and the power industry in effect is committed to serve it. It should do so as rapidly and as profitably as possible. There remains a sizable portion of the industry which is not so served, and which has the management and capital to take advantage of this advance in melting practice.

L. W. Clark's paper clearly discusses the characteristics of the electric arc melting furnace load and the means of serving it satisfactorily. With this important data available to the utility there should be no difficulty in estimating the cost of serving a load which will yield a return of 20 dollars to 40 dollars per kw-year.

In fact, the load is not too bad and it offers a comparatively new field of revenue to the utilities.

# Induction Heating at Low Temperatures

**Discussion of a paper by E. L. Bailey published in the November 1935 issue, pages 1210–12, and presented for oral discussion at the electrochemistry and electrometallurgy session of the winter convention, New York, N. Y., January 29, 1936.**

**F. T. Chesnut** (Ajax Electrothermic Corp., Trenton, N. J.): This paper is not only well written but also covers a very interesting development. The company with which the writer is connected has worked closely with E. L. Bailey on his induction oven program. From what has been learned from the men who are operating these equipments day in and day out, it is felt that the author has understated the features of safety, excellent working conditions, and low maintenance. The men who work with them certainly are most enthusiastic on these points.

It is noticed that the author usually refers to metal parts. Our idea is that the ovens will be used largely for magnetic metal parts, because with nonmagnetic metals there will be a tendency for temperatures to lack uniformity. The writer believes that this type of oven is inherently of the continuous type rather than the batch type, since motion through the coils is required to obtain uniform temperatures.

In its application to baking of finishes on painted parts, the oven is essentially a quality tool where better finish and less floor space justify a higher initial cost.

# News
## Of Institute and Related Activities

## North Eastern District Meeting and Student Branch Convention

THE 3 day meeting of the North Eastern District of the A.I.E.E. to be held in New Haven, Conn., from Wednesday to Friday, May 6–8, promises not only a highly interesting technical program, but also a widely varied schedule of activities during the intervals between technical sessions. Headquarters for the meeting, which will be combined as usual on Friday with the Student Branch convention, will be magnificent Strathcona Hall, Yale University, and those attending will have full opportunity to visit also some of the other best-known buildings of the university.

Famous as the home of Yale, New Haven is also an important industrial center, with many well-known industries located within the city limits and many more situated in cities or towns only a few minutes away by automobile, trolley, train, or bus. Interesting trips to many of these establishments, trips to the Yale buildings and other points of historical interest, and scenic drives through East and West Rock Parks and along the shore are being arranged. It was in New Haven that Eli Whitney manufactured his cotton gins and later started a gun factory, the first factory in the country to introduce the revolutionary principle of standardized parts and division of labor. Here too was opened, in 1878, the first commercial telephone exchange in the world, and here Samuel F. B. Morse, a student in Yale's class of 1810, received his first impetus in electrical studies.

Table I—Hotel Rates

| | Single Rooms | | Double Rooms | |
|---|---|---|---|---|
| Hotel | Without Bath | With Bath | Without Bath | With Bath |
| Taft | $2.00 | $3.00 | $4.00 | $5.00 |
| Garde | 1.50–2.00 | 2.50 | 2.50 | 3.50–5.00 |
| Duncan | 2.00 | 2.50 | 2.50 | 3.00–3.50 |
| Bishop | 2.00 | 2.50 | | 4.00 |

REGISTRATION—HOTELS

Everyone planning to attend the meeting is urged to register in advance by mail if possible. Advance registrations should be sent to C. H. Clements, The Southern New England Telephone Company, P. O. Box 1562, New Haven, Conn. Registrations should be completed at Strathcona Hall, at the corner of Grove and Prospect Streets, between 9 and 10 o'clock on the morning of May 6. The city of New Haven will be on daylight saving time.

Excellent hotel accommodations are available at the Hotel Taft, Hotel Duncan, and Hotel Bishop, all near the New Haven Green, and at the Hotel Garde, which is directly opposite the railroad station. Schedules of rates may be found in table I. Visitors are requested to make their own hotel reservations, dealing direct with the hotel they prefer. Student counselors will be advised of special arrangements to be made for the accommodation of students.

ACTIVITIES SCHEDULED

At 10 a.m. on Wednesday, Vice President W. H. Timbie of the North Eastern District will welcome those in attendance. The opening session that morning will be devoted to addresses and a paper related to the problem of developing proper visibility on highways. During the general session in the afternoon, starting at 2 o'clock, an address and 4 papers on a variety of subjects will be presented. In the afternoon, it has been arranged that those who wish to visit some of the Yale buildings—the library, graduate school, and gymnasium— may do so with the help of trained guides; in the evening, a trip to the main central office of The Southern New England Telephone Company is planned for all who would care to inspect the dial switching equipment. It is thought that many will find such a trip especially timely because one of the papers to be presented in the afternoon will deal with dial switching of toll calls.

The technical session on Thursday morning will open at 9:30. Three most interesting subjects are on the program. For the afternoon, plans have been made for an inspection of the latest transportation equipment of the New York, New Haven and Hartford Railroad, following which a special train will leave on an inspection trip to the Wallingford Steel Company, manufacturers of cold rolled steel products. At Wallingford also there will be opportunity to visit the plant of R. Wallace and Sons Manufacturing Company, makers of sterling silverware. Students are urged to come on Thursday in time for this afternoon inspection program. In the evening an informal dinner meeting will be held at the New Haven Lawn Club, only 5 blocks from the meeting headquarters. Although in the heart of the city, a club atmosphere will prevail. The dinner will be followed by entertainment and dancing.

Friday morning will be devoted to a student technical session, and at noon there will be a luncheon conference of counselors and Branch chairmen. Arrangements are being made for a variety of student inspection trips in the afternoon, to manufacturing establishments and various departments of Yale University. At Strathcona Hall, starting at 2 o'clock, the third and final technical session will be held. In the evening, it is expected that a special entertainment feature will be presented.

On Saturday there will be an especially interesting trip to the plant of the Sikorsky Aircraft Company in Bridgeport, only 18 miles from New Haven.

Arrangements also have been made for a golf tournament to be held at a nearby country club. Prizes will be awarded.

Courtesy *Yale Alumni Weekly*

**Strathcona Hall and Sterling Tower, Yale University, headquarters for the forthcoming A.I.E.E. North Eastern District meeting**

## Program

Daylight Saving Time

For the papers that have been published in Electrical Engineering reference to the issue and page is given.

### Wednesday, May 6

**9:00 a.m.—Registration**

**10:00 a.m.—Opening Session; Highway Lighting**

Address of Welcome, W. H. Timbie, vice-president, North Eastern District, A.I.E.E.

Address: Optical Principles and Light Sources for Highway Lighting, C. A. B. Halverson, General Electric Co.

Address: The Need for Better Visibility on Highways by Night, L. A. S. Wood, Westinghouse Electric and Mfg. Co., and President, Illuminating Engineering Society.

*Polarized Light for Headlamps, H. T. Rights, Westinghouse Electric and Mfg. Co., and Robert Sparks, Hartford Public High School.

**2:00 p.m.—General Session**

Electrical Studies of Living Tissue, A. G. Conrad, B. R. Teare, and H. W. Haggard, Yale University.

*Aging in Copper Oxide Rectifiers, E. A. Harty, General Electric Co.

Dial Switching of Toll Calls in Connecticut, W. F. Robb, A. M. Millard, and G. M. McPhee, The Southern New England Telephone Co.

**8:00 p.m.—Visit to S.N.E. Telephone Co., Dial Switching**

### Thursday, May 7

**9:30 a.m.—General Session**

Address: Public Utility Problems, Samuel Ferguson, president, Hartford Electric Light Co.

*Shunt Capacitors on Distribution Circuits, F. M. Starr, General Electric Co., and G. P. Gamble, Union Electric Light and Power Co.

Electrical Apparatus for Diesel Cars, G. F. Smith, Westinghouse Electric and Mfg. Co. April, p. 335–41

**12:00 noon—District Executive Committee Luncheon**

**2:00 p.m.—Inspection Trips**

Transportation equipment of New York, New Haven and Hartford Railroad at New Haven railroad station.

Special train to Wallingford Steel Company and R. Wallace and Sons Mfg. Co.

**7:00 p.m. Informal Meeting**

Dinner at the New Haven Lawn Club followed by special entertainment and dancing.

### Friday, May 8

**9:00 a.m.—Student Technical Session**

**12:00 noon—Luncheon Conference of Counselors and Branch Chairmen**

**1:45 p.m.—Student Inspection Trips**

**2:00 p.m.—General Session**

Surge Protectors for Current Transformers, G. Camilli and L. V. Bewley, General Electric Co. March, p. 254–60

Equivalent Circuits—2 Coupled Circuits, J. C. Balsbaugh, Massachusetts Institute of Technology, W. P. Douglass, The Procter and Gamble Co., R. B. Gow, Kansas Gas and Electric Co., and A. H. Leal, Rio de Janeiro. April, p. 366–71

Switching Surges in Rotating Machines, J. F. Calvert and F. D. Fielder, Westinghouse Electric and Mfg. Co. April, p. 376–84

Tests on Lightning Protection for A-C Rotating Machines, E. M. Hunter, General Electric Co. Feb., p. 137–44

**8:00 p.m.—Special Entertainment Feature**

### Saturday, May 9

Inspection trip to Sikorsky Aircraft Co., Bridgeport, Conn.

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* These papers are scheduled for presentation, but they have not been accepted for publication at the time of going to press.

### LADIES PROGRAM

As this announcement goes to press, a committee is engaged in developing a program for the ladies which will include full opportunity for social diversion and entertainment, as well as visits to points of outstanding interest.

### RULES ON PRESENTING AND DISCUSSING PAPERS

At the technical sessions, papers may be presented in abstract, 10 minutes being allowed for each paper unless otherwise arranged or the presiding officer meets with the authors preceding the session to arrange the order of presentation and allotment of time for papers and discussion.

Any member is free to discuss any paper when the meeting is thrown open for general discussion. Usually 5 minutes is allowed to each discusser for the discussion of a single paper or of several papers on the same general subject. When a member signifies his desire to discuss several papers not dealing with the same general subject, he may be permitted to have a somewhat longer time.

It is preferable that a member who wishes to discuss a paper give his name in advance to the presiding officer of the session at which the paper is to be presented. Each discusser is to step to the front of the room and announce, so that all may hear, his name and professional affiliations. Three typewritten copies of discussion prepared in advance should be left with the presiding officer.

Other discussions to be considered for publication should be typewritten (double spaced) and submitted in triplicate to C. S. Rich, secretary of the technical program committee, A.I.E.E. headquarters, 33 West 39th St., New York, N. Y., on or before May 22, 1936. Discussion of addresses and papers which is not for publication need not be submitted for consideration.

### COMMITTEES

**General Meeting Committee:** W. H. Timbie, vice president, North Eastern District, *chairman;* A. C. Stevens, secretary-treasurer, North Eastern District; W. B. Hall, chairman of student counselors, North Eastern District; and E. K. Huntington, B. K. Northrop, H. H. Race, and R. H. Van Horn.

**Program Committee:** R. G. Warner, *chairman;* C. T. Hughes and H. W. Sundius.

**Hotels and Registration Committee:** C. H. Clements, *chairman;* A. G. Conrad, W. J. Mahan, A. M. Millard, C. A. Moisberry, and W. F. Robb.

**Entertainment Committee:** C. J. Daly, *chairman;* H. O. Anderson, F. A. Faron, C. N. Gregory, T. J. Russell, and B. R. Teare.

**Ladies Program Committee:** Mrs. Sidney Withington, *chairman;* Mrs. S. H. Barnum, Mrs. A. F. Brooks, Mrs. E. H. Everit, Mrs. S. R. McCandless, and Mrs. B. R. Teare.

**Inspection Trips Committee:** E. D. Lynch, *chairman;* G. E. Hulse, M. M. Marks, J. A. Nixon, J. P. Powell, J. H. Spraggon, and Sidney Withington.

**Publicity Committee:** R. S. Judd, *chairman;* P. A. Borden, R. D. Cutler, C. R. Harte, P. C. Mabon, C. W. Taggart, and H. M. Turner.

## A.I.E.E. Executive Committee Meets

A meeting of the executive committee of the American Institute of Electrical Engineers was held at Institute headquarters, New York, N. Y., March 9, 1936, in place of the regular meeting of the board of directors.

The following were present: President E. B. Meyer (chairman), F. M. Farmer, Everett S. Lee, W. I. Slichter, R. H. Tapscott, and J. B. Whitehead, members of the committee; C. R. Jones, director; H. H. Henline, national secretary.

Report was made of action by the executive committee, as of February 14, 1936, in transferring 6 applicants to the grade of Fellow; electing 12 and transferring 27 applicants to the grade of Member; electing 69 to the grade of Associate; and in enrolling 82 students.

A report was presented and approved of a meeting of the board of examiners held February 19, 1936. Upon the recommendation of the board of examiners, the following actions were taken: 4 applicants were transferred and 1 was re-elected to the grade of Fellow; 23 applicants were transferred and 18 were elected to the grade of Member; 73 applicants were elected to the grade of Associate; 68 Students were enrolled.

The finance committee reported disbursements in February amounting to $19,436.73; report approved.

Everett S. Lee, chairman of the National membership committee, reported a 19 per cent increase in the number of applications received since May 1935 over the number received during the same period of the previous year.

Report was made that the dates of the South West District meeting to be held in Dallas next fall had been changed by the District officers from November 2–4 to October 26–28.

Upon the recommendation of the committee on Student Branches, authority was granted for the establishment of a Student Branch of the Institute at the University of Maryland, College Park.

The national nominating committee reported its selection of the official ticket of nominees for election to Institute offices becoming vacant August 1, 1936. (Information regarding the nominees was published in the March issue of ELECTRICAL ENGINEERING.)

Upon the recommendation of the standards committee, approval was given to the report of the sectional committee on proposed "Standards for Railway Motors and Other Rotating Electrical Machinery on Rail Cars and Locomotives," *C*-35, and the committee voted to accept indorsing sponsorship of the sectional committee on preferred numbers.

The appointment of the following representatives, upon the recommendation of the standards committee, was reported and approved: M. E. Noyes as chairman of the sectional committee on aluminum, *C*-11, and chairman of the A.I.E.E. delegation on that committee; E. B. Paxton as a member of the A.I.E.E. delegation on the sectional committee on transformers; and C. T. Sinclair as the A.I.E.E. representative on the committee on grounding formed under the auspices of the American Water Works Association in co-operation with the Edison Electric Institute.

Upon the recommendation of the committee on research, it was voted that the Institute should act as sponsor for a research project in "electric shock" at Johns Hopkins University, under the direction of Professor W. B. Kouwenhoven and his associates on the medical school staff, and apply to The Engineering Foundation for a grant of money for this project, and, also, for a research project in "Stabilization of Impregnated Paper Insulation," to be carried on at Johns Hopkins University under the direction of Dr. J. B. Whitehead.

Vice President W. H. Harrison, of the Middle Eastern District, was designated as the representative of the Institute upon the occasion of the celebration, on March 20, of seventy years of engineering at Lafayette College.

Local Honorary Secretary A. F. Enstrom, of Sweden, was appointed the delegate of the Institute to attend the celebration, in Stockholm, on May 19–20, of the 75th anniversary of the foundation of Svenska Teknologforeningen.

Other matters were discussed, reference to which may be found in this or future issues of ELECTRICAL ENGINEERING.

# Summer Convention Offers Vacation Trip Possibilities

THE A.I.E.E. summer convention, which will be held at Pasadena, Calif., June 22–26, 1936, with headquarters in the Huntington Hotel, affords members and their guests unusual opportunities. The technical program will combine the latest experiences of both eastern and western engineers. Pasadena and its environs provide splendid scenery, not to mention the trip through the Rocky Mountains from points east. As usual, the program will include sports, trips, and entertainment features. In addition, there is the California Pacific International Exposition at San Diego, and Sunday, June 28, has been designated as "electrical engineers day." Those planning to take advantage of these opportunities no doubt will be interested in the further development of plans for a special train, which were announced tentatively in the March issue of ELECTRICAL ENGINEERING.

## TECHNICAL SESSIONS

Tentative arrangements provide for 10 or 11 technical sessions which will treat such subjects as engineering education, illumination, electrophysics, conductor vibration, protective devices, power transmission, rotating electrical machinery, transformers, and selected subjects.

The transformer symposium will be well rounded from the point of view of both design and application. The world's largest power transformers for 288 kv will be described as well as modern high voltage power transformer design. Other papers will deal with the impulse strength of transformers, the selection of insulation, regulation, the application of overrefined oils, and the application of modern distribution transformers.

The selected subjects session, as tentatively planned, should prove of unusual interest to those concerned with electrical measurements and the physiological effects of electric shock. Professor Sorensen and Simon Ramo will present further test results on nonarcing sphere gaps. Another paper from the Pacific Coast, by Otto A. Knopp, will deal with precision instrument transformers. Two of the papers on electric shock are by well-known Institute authors collaborating with medical doctors from the college of physicians and surgeons, Columbia University, New York, N. Y., and from The Johns Hopkins University, Baltimore, Md.

The technical program and other details will be announced in the May issue of ELECTRICAL ENGINEERING.

## TRIPS TO MT. WILSON AND CALIFORNIA PACIFIC EXPOSITION

One very interesting trip which will be scheduled for an evening will be to the astronomical observatory on Mt. Wilson, about an hour's drive from Pasadena over a new "high gear" highway. Both the observatory and the view of the cities and valley below are attractive features. Tentative plans for the evening's entertainment include a dinner at the Mt. Wilson Hotel, an illustrated lecture on astronomy and the observatory, and an opportunity to look through the 60 inch telescope, besides the inspiring view from this mountain top before and after dark.

The 1936 California Pacific International Exposition is a creation of cultural and physical beauty set amid beautiful Balboa Park at San Diego, 125 miles south of Pasadena, with 1,400 acres of landscaped grounds. Sunday, June 28th, has been designated as "electrical engineers day" at the exposition.

The new Palace of Electricity will be the mecca for skilled scientists and technicians. It contains many exhibits depicting progress and developments in electrical machinery for the home, many other labor-saving devices, a model of the electrically operated ship "President Coolidge," new models of street railway system equipment, and scientific marvels of the laboratory.

Perhaps the greatest appeal of all will be found in the lighting system which "paints" the grounds. Requiring a total of 4,000 kw when in full operation, the lighting exhibit itself comprises a complete exposition of color, effect, and beauty. Subtropical palms and flowers are bathed in pastel shades. "Firefly" lights twinkle high in treetops over Alcazar Gardens, as batteries of powerful lights pour gleaming multi-colored beams against the buildings.

The many other exhibit palaces and arrangements for amusement hold much of unusual interest for visitors.

## SPECIAL TRAIN SUGGESTED

It has been suggested from several sources that the trip to the summer convention for those members who would pass through Chicago provides a wonderful opportunity for an organized party to visit many points of interest, particularly to engineers. If a sufficient number signify such interest a special train could be provided. This arrangement should be a further inducement to attend the convention, as one could make the round trip with friends and be free of all bother with annoying details. On the way out one could see the famous Boulder Dam, then after a week at Pasadena, take in on the return trip Bonneville and the Grand Coulee projects on the Columbia River in Washington and the magnificent national reservation, Glacier Park. For the round trip, commencing and terminating at Chicago, the approximate cost (for one person in a lower berth) would be $200 (expenses at Pasadena while attending the convention not included). A suggested itinerary with dates and time required follows. Those interested should write to National Secretary H. H. Henline, 33 West 39th Street, New York, N. Y. If the response warrants it, the tour will be arranged and those who have written will be advised of final details and costs.

## TENTATIVE ITINERARY

**Wednesday, June 19**

Leave Chicago, Ill., via The Milwaukee Road.................... 7:30 p.m.

**Thursday, June 18**

Arrive Omaha, Neb., via The Milwaukee Road.................... 7:30 a.m.
Leave Omaha, Neb., via Union Pacific System........................10:20 a.m.

**Friday, June 19**

Arrive Las Vegas, Nev., via Union Pacific System.................. 9:30 p.m.

**Saturday, June 20**

At Boulder Dam.
Leave Las Vegas, Nev., via Union Pacific System.................. 9:50 p.m.

**Sunday, June 21**

Arrive Pasadena, Calif., via Union Pacific System.................. 8:50 a.m.

**Monday—Friday, June 22–26—**
**Attending convention**

**Friday, June 26**

Leave Los Angeles, Calif., via Southern Pacific Lines................ 8:30 p.m.

**Saturday, June 27**

Arrive San Francisco, Calif., via Southern Pacific Lines............ 9:00 a.m.
Sightseeing.
Leave San Francisco, Calif., via Southern Pacific Lines............ 6:20 p.m.

**Sunday, June 28**

Arrive Portland, Ore., via Southern Pacific Lines..................... 3:45 p.m.
Motor to Bonneville Dam, Wash.
Leave Bonneville via Union Pacific System.........................10:00 p.m.

**Monday, June 29**

Arrive Spokane, Wash., via Union Pacific System.................. 7:00 a.m.
Motor to Grand Coulee Dam.
Overnight stop.

**Tuesday, June 30**

Leave Spokane, Wash., via Great Northern Railway................ 7:45 a.m.
Arrive Belton, Mont., via Great Northern Railway............... 4:45 p.m.
Motor to Lake McDonald, Glacier Park.
Overnight at Lake McDonald Hotel.

**Wednesday, July 1**

In Glacier Park.
Leave Lake McDonald Hotel via Motor.......................... 8:30 a.m.
Arrive Going-to-the-Sun Chalets via Motor..........................11:00 a.m.
Leave Going-to-the-Sun Chalets via Motor.......................... 3:45 p.m.
Arrive Many Glaciers Hotel via Motor.......................... 5:05 p.m.
Overnight at Many Glaciers Hotel.

**Thursday, July 2**

Motor to Glacier Park Hotel.
Motor to 2 Medicine Lake and launch trip.
Leave Glacier Park via Great Northern Railway............... 6:53 p.m.

**Friday, July 3**

Arrive St. Paul, Minn., via Great Northern Railway...............10:30 p.m.
Leave St. Paul, Minn., via The Milwaukee Road................11:49 p.m.

**Saturday, July 4**

Arrive Chicago, Ill., via The Milwaukee Road.................... 7:50 a.m.

**Annual Convention of American Transit Association.** The 55th annual convention of the American Transit Association and its affiliates will be held September 20–23, 1936, at White Sulphur Springs, W. Va. The convention is expected to bring together delegates representing more than 90 per cent of the transit operations in the United States, Canada, and Mexico, and all companies engaged in the manufacture of related transit equipment; plans are reported to be well under way. Further details may be obtained from Robert B. Fentress, American Transit Association, 292 Madison Avenue, New York, N. Y.

## Future AIEE Meetings

**North Eastern District Meeting,**
New Haven, Conn., May 6–8, 1936

**Summer Convention,**
Huntington Hotel, Pasadena, Calif., June 22–26, 1936

**South West District Meeting,**
Dallas, Texas, Oct. 26–28, 1936

**Southern District Meeting,**
Birmingham, Ala., Dec. 1936

# A Group of Institute Leaders Visits the South West

PRESIDENT E. B. Meyer, National Secretary H. H. Henline, and Editor G. Ross Henninger (left to right) as they appeared while inspecting the Texas Centennial Exposition grounds upon the occasion of their visit to the A.I.E.E. Dallas Section on March 23, 1936; they visited various Sections and Student Branches in the Institute's South West District and adjoining territory. The party was taken to the exposition grounds as guests of Past-Vice President B. D. Hull and L. B. Starbird, chairman of the Dallas Section; they were shown around the 187-acre $25,000,000-project by director of works Ray Foley. The exposition is scheduled to open in June and will be one of the attractions for those who will attend the Institute's South West District meeting to be held in Dallas, October 26–28, 1936.

## Fiftieth Anniversary of Electrolytic Aluminum

On the evening of February 17, 1936, the Electrochemical Society sponsored a dinner meeting at the Waldorf-Astoria Hotel in New York, N. Y., to celebrate the fiftieth anniversary of the discovery of the electrolytic process of producing aluminum. The story of the discovery, which Charles Martin Hall (deceased 1914) achieved at the age of 22, was retold by those who knew him well, and its significance was interpreted by eminent scientists. The transition of aluminum in the short space of 50 years from a semiprecious metal to a household and industrial commonplace was emphasized to demonstrate the importance of Hall's achievement on the morning of February 23, 1886.

Hall was a son of a Congregational minister, and early evidenced an intense interest in chemistry. He fitted up a makeshift laboratory in the woodshed in the back yard of his father's humble home in Oberlin, Ohio, since his funds for procuring laboratory equipment were limited. It was there that Hall made his memorable discovery which reduced the price of aluminum from $8 per pound to $2, and which marked the beginning of the first and largest electrochemical industry. In spite of the great reduction in cost that the Hall process made possible, the metal was not put to any immediate extensive use, because its properties still were comparatively unknown, and engineers, although interested, were skeptical about applying it to their designs. Within a few years, however, its many advantages became known, and then followed a period in which the public's imagination literally ran away. Men freely predicted aluminum bridges, aluminum trains, buildings, and airships, not realizing the many and difficult problems still to be solved before such things could be realized. Today, after 50 years, many of these rash early prophecies are being fulfilled, and almost day by day new uses are being found for this versatile metal and the many aluminum alloys that have been developed.

**Seventieth Anniversary of Engineering at Lafayette.** On March 20, 1936, the seventieth anniversary of engineering at Lafayette College, Easton, Pa., was celebrated by a special all-day program with addresses by noted engineers among whom were several prominent Institute members. Engineering instruction was offered at this institution for the first time during the 1865–66 college term. W. H. Harrison, vice president of the A.I.E.E. Middle Eastern District, was designated as the Institute's official representative to the celebration. The event was accompanied by an engineering and industrial exhibition of machines and methods employed in modern engineering and a display of its products, including working models illustrating manufacturing processes. This exhibition was open from March 18 to 21, inclusive. Prof. Moreland King (A'06, F'25) of the department of electrical engineering at Lafayette was general chairman of the anniversary committee.

## To Institute Members Planning Trips Abroad

Members of the Institute who contemplate visiting foreign countries are reminded that since 1912 the Institute has had reciprocal arrangements with a number of foreign engineering societies for the exchange of visiting member privileges, which entitle members of the Institute while abroad to membership privileges in these societies for a period of 3 months and members of foreign societies visiting the United States to the privileges of Institute membership for a like period of time, upon presentation of proper credentials. A form of certificate which serves as credentials from the Institute to the foreign societies for the use of Institute members desiring to avail themselves of these exchange privileges may be obtained upon application to Institute headquarters, New York. The members should specify which country or countries they expect to visit, so that the proper number of certificates may be provided, one certificate being addressed to only one society.

The societies with which these reciprocal arrangements have been established and are still in effect are: Institution of Electrical Engineers (Great Britain), Société Française des Electriciens (France), Association Suisse des Electriciens (Switzerland), Associazione Elettrotecnica Italiana (Italy), Koninklijk Instituut van Ingeniurs (Holland), Verband Deutscher Elektrotechniker E. V. (Germany), Norsk Elektroteknisk Forening (Norway), Svenska Teknologforeningen (Sweden), Stowarzyszenie Elektrykow Polskich (Poland), Elektrotechnicky Svaz Ceskoslovensky (Czechoslovakia), The Institution of Engineers, Australia (Australia), Denki Gakkwai (Japan), and South African Institute of Electrical Engineers (South Africa).

**Maps on Electric Utilities Available.** The Federal Power Commission, Washington, D. C., has announced the availability of 2 maps in color on electric utilities. The first shows "service areas" or territories served by the companies owned and controlled by the principal holding companies and other important electric utility systems. The second shows the principal generating plants and transmission lines of the United States.

## N.E.M.A. Publishes Joint Report on Radio Noise

The Joint Co-ordination Committee on Radio Reception, consisting of representatives of the Edison Electric Institute, the National Electrical Manufacturers Association and the Radio Manufacturers Association, has issued a report entitled "Methods of Measuring Radio Noise" (N.E.M.A. Publication No. 102). The report sets up the instrument specifications for measuring radio noise and the procedure to be followed in the use of such instrument.

Those who should have occasion to make use of the report are persons engaged in radio transmission and reception, manufacturers of devices that give rise to radio noise and users of these devices—in fact, anyone interested in improving the art of radio or in determining quantitatively the value of noise radiation. The text is illustrated by curves and wiring diagrams. Copies may be procured at 35 cents each from National Electrical Manufacturers Association, 155 East 44th Street, New York, N. Y.

## Membership Applications Show Increase

Applications for membership in the A.I.E.E. received at Institute headquarters during the 10 months from May 1935 to March 1936 were 19.1 per cent higher than those received during the same period a year earlier, according to the March report of the national membership committee. Applications from Enrolled Students whose periods of enrolment had expired were 10.3 per cent higher, and those from all others were 26.7 per cent higher, the report showed. Of the 1,323 Students invited this year to apply for admission to the Associate grade, 558, or 42 per cent, had applied by March 1; returns for the previous year indicated that only 40 per cent of those eligible applied. A summary of the results shows:

| | Applications Received May to March | | |
|---|---|---|---|
| | 1934–35 | 1935–36 | Per Cent Increase |
| From Students | 506 | 558 | 10.3 |
| From all others | 589 | 746 | 26.7 |
| Total | 1,095 | 1,304 | 19.1 |

| | August to March | |
|---|---|---|
| | 1934–35 | 1935–36 |
| Reinstatements | 480 | 483 |

Details of the report are shown in the accompanying tabulation.

**Report of A.I.E.E. National Membership Committee, March 1936**

| Sections | Applications Received, May to March 1935–36 | Applications Received, May to March 1934–35 | Section Membership, Aug. 1, '35 | Reinstatements since Aug. 1, '35 |
|---|---|---|---|---|
| **District 1** | | | | |
| Boston | 29 (17) | 26 (14) | 378 | 8 |
| Connecticut | 25 (12) | 19 (15) | 225 | 11 |
| Ithaca | 3 (2) | 7 (6) | 56 | 1 |
| Lynn | 10 (3) | 6 (4) | 99 | 8 |
| Niagara Frontier | 12 (4) | 59 (6) | 197 | 4 |
| Pittsfield | 14 (2) | 4 (2) | 107 | 4 |
| Providence | 4 (2) | 10 (4) | 85 | 2 |
| Rochester | 4 (0) | 11 (3) | 71 | 3 |
| Schenectady | 43 (26) | 34 (23) | 353 | 10 |
| Springfield | 6 (5) | 4 (2) | 65 | 2 |
| Syracuse | 7 (3) | 6 (2) | 65 | 1 |
| Worcester | 9 (7) | 4 (3) | 62 | 1 |
| | 166 (83) | 190 (84) | 1,763 | 55 |
| **District 2** | | | | |
| Akron | 4 (2) | 3 (1) | 64 | 3 |
| Baltimore | 14 (10) | 17 (13) | 167 | 9 |
| Cincinnati | 18 (7) | 11 (6) | 143 | 0 |
| Cleveland | 29 (13) | 23 (12) | 220 | 9 |
| Columbus | 8 (6) | 5 (5) | 62 | 1 |
| Erie | 3 (2) | 3 (2) | 48 | 4 |
| Lehigh Valley | 18 (10) | 26 (7) | 185 | 6 |
| Philadelphia | 46 (19) | 32 (19) | 517 | 34 |
| Pittsburgh | 18 (12) | 18 (9) | 379 | 24 |
| Sharon | 10 (3) | 6 (3) | 55 | 2 |
| Toledo | 8 (3) | 13 (1) | 69 | 5 |
| Washington, D. C. | 26 (11) | 23 (2) | 229 | 10 |
| | 202 (98) | 180 (80) | 2,138 | 107 |
| **District 3** | | | | |
| Mexico | 9 (0) | 3 (1) | 66 | 4 |
| New York | 311 (86) | 209 (97) | 2,773 | 134 |
| | 320 (86) | 212 (98) | 2,839 | 138 |
| **District 4** | | | | |
| Alabama | 5 (1) | 5 (3) | 38 | 1 |
| Atlanta | 3 (1) | 4 (1) | 71 | 0 |
| Florida | 15 (5) | 6 (3) | 47 | 1 |
| Louisville | 1 (1) | 12 (7) | 56 | 3 |
| Memphis | 3 (1) | 1 (0) | 31 | 5 |
| New Orleans | 8 (5) | 6 (2) | 44 | 2 |
| North Carolina | 10 (4) | 5 (3) | 78 | 4 |
| Virginia | 7 (5) | 14 (2) | 86 | 3 |
| | 52 (23) | 53 (21) | 451 | 19 |
| **District 5** | | | | |
| Chicago | 34 (16) | 34 (17) | 614 | 23 |
| Central Indiana | 14 (9) | 10 (1) | 94 | 3 |
| Detroit-Ann Arbor | 42 (17) | 23 (14) | 268 | 13 |
| Fort Wayne | 3 (0) | 5 (4) | 55 | 0 |
| Iowa | 8 (7) | 6 (6) | 50 | 1 |
| Madison | 3 (2) | 4 (4) | 51 | 3 |
| Milwaukee | 27 (15) | 17 (10) | 173 | 10 |
| Minnesota | 3 (2) | 6 (5) | 74 | 3 |
| Urbana | 0 (0) | 1 (1) | 36 | 1 |
| | 134 (68) | 106 (62) | 1,415 | 57 |
| **District 6** | | | | |
| Denver | 10 (4) | 11 (7) | 138 | 7 |
| Nebraska | 2 (1) | 8 (5) | 51 | 3 |
| | 12 (5) | 19 (12) | 189 | 10 |
| **District 7** | | | | |
| Dallas | 10 (2) | 8 (2) | 87 | 7 |
| Houston | 7 (2) | 13 (5) | 65 | 3 |
| Kansas City | 14 (8) | 14 (9) | 134 | 5 |
| Oklahoma City | 24 (12) | 18 (6) | 110 | 4 |
| St. Louis | 37 (15) | 8 (4) | 182 | 3 |
| San Antonio | 5 (2) | 2 (1) | 26 | 4 |
| | 97 (41) | 63 (27) | 604 | 26 |
| **District 8** | | | | |
| Los Angeles | 50 (24) | 42 (23) | 385 | 21 |
| San Francisco | 45 (21) | 24 (11) | 373 | 11 |
| | 95 (45) | 66 (34) | 758 | 32 |
| **District 9** | | | | |
| Montana | 5 (3) | 5 (5) | 34 | 2 |
| Portland | 16 (7) | 13 (4) | 92 | 3 |
| Seattle | 27 (17) | 12 (9) | 117 | 12 |
| Spokane | 7 (4) | 8 (2) | 44 | 2 |
| Utah | 2 (1) | 4 (3) | 39 | 2 |
| | 57 (32) | 42 (23) | 326 | 21 |
| **District 10** | | | | |
| Saskatchewan | 4 (0) | 3 (0) | 24 | 0 |
| Toronto | 15 (8) | 13 (2) | 286 | 15 |
| Vancouver | 10 (4) | 10 (4) | 88 | 3 |
| | 29 (12) | 26 (6) | 398 | 18 |
| Totals: | | | | |
| Section territory | 1,164 (493) | 957 (447) | 10,881 | 483 |
| Non-Section territory | 140 (65) | 138 (59) | 1,714 | |
| Grand Total | 1,304 (558) | 1,095 (506) | 12,595 | |

NOTE: Following the number of applications reported for the month or period is indicated within parentheses the number of these applications received from Enrolled Students upon expiration of enrolment.

# Power Group and Other Group Activities of the Institute's New York Section

**A report of the development of group activities in the A.I.E.E. New York Section prepared especially for ELECTRICAL ENGINEERING by F. P. West (A'25), chairman of the power group of the New York Section, 1935–36, and H. E. Farrer (A'21), a member of A.I.E.E. headquarters staff.**

MANY of those who have been responsible for carrying on the work of the Institute's New York Section for the 10 years following its establishment in 1919 were impressed with the need of an expansion of activity and service beyond that involved in the holding of the usual 8 general meetings.

The New York Section comprises 20 to 25 per cent of the national membership and represents a fair cross section of the field of electrical engineering. It was therefore advisable to provide subjects for the meetings which could be treated in a very general manner so that they would appeal to the members engaged in lines of engineering other than those discussed. This prevented, to a large degree, the detailed presentation and discussion of technical problems specific to certain fields of engineering that were represented by large groups of members, such as those engaged in the development of facilities pertaining to the fields of power, transportation, communication, lighting, and other similar classes. There was thus lost to the men in such groups great educational opportunities to improve their knowledge along the lines of endeavor in which they actually were employed.

An expansion of activity and an increase in the number of meetings would result in giving to a far greater number of members a personal part in the Section program, both technical and administrative.

In view of the foregoing considerations, it was decided to divide the Section, as far as main fields of interest were concerned, into groups; and in April 1929 the executive committee arranged for the establishment of the communication, illumination, power, and transportation groups.

Appreciating that in seeking a method of increasing Section activities by subdivision and specialized development of group interests there also might have been created a tendency, altogether too prevalent today in practically all fields including engineering, to forget that fundamental principle for successful organization operation so effectively expressed in the phrase "in union there is strength," it was agreed also that whatever specialized activities were set up by and for any group participation should be open to the entire Section membership. That this decision was a wise one is evidenced by the very considerable attendance at many group meetings of members of each of the other 3 groups, and also by the general development of interest in the New York Section as a whole and in membership in the national organization.

It might be well to point out here that the activities of all 4 groups are subject to the review, co-ordination and approval of the executive committee of the Section itself. To date, however, official supervision has consisted largely in the allocation to the groups of the number and dates of meetings. This is necessary in order that the Section budget be not exceeded, as well as to insure a complete Section program without conflicting meeting dates.

In a recent review of Section and group activities, the executive committee became so impressed with the wonderful results obtained by the group organizations in following through the plans for expansion that they felt a description of the efficient operation of one of the groups, for instance, the power group, might be of interest and value to other A.I.E.E. Sections. Hence, in the following paragraphs there is given a somewhat general outline of power group activities as now carried on.

## POWER GROUP ACTIVITIES

The power group organization is officered by an elected chairman, a vice chairman, and a secretary, together with an executive committee. Three operating committees are appointed as follows: program, publicity, and related activities; these, with the executive committee, comprise a total personnel of 34. The executive committee serves as the co-ordinating body to which the other 3 committees report. The program committee handles all arrangements for the technical meetings, including the selection of subjects and speakers. The related activities committee has devoted a large amount of time to the planning and carrying out of inspection trips, although other activities, really the side lines in the group program, come within its scope. For instance, they set up a course in structures to aid engineers applying for a professional license; the registration was more than 170. The interest in this course was such that 2 new classes are now in operation. Then there is an effective speaking course also in session, and a review course in electrical engineering; one in electronics is getting under way. Courses in such subjects as economics and business law, as well as a golf tournament and other entertainment features, are under consideration.

The publicity committee prepares special notices and posters of power group events and arranges for their placement on the bulletin boards of the electrical industry in New York City. For this purpose they have built up a comprehensive list of men who regularly attend to this work in the Section territory. These special notices are of course adjuncts to the notices always mailed to the entire section membership each month, and have served very effectively in building up meeting attendance. The committee also prepares written accounts of proposed and past meetings for the press.

The technical meetings of the power group, of which there have been 4 allocated each year to date, have enjoyed unusual success, both as to attendance (averaging more than 400), and from the viewpoint of the extremely effective presentation and discussion of technical papers by some of the younger engineers. One of the meetings of particular interest each year has a volunteer paper program, consisting entirely of papers selected from voluntary submissions.

In having provided this medium (the 4 group organizations) for the presentation and active discussion of papers by the younger engineers, something almost entirely absent formerly under the 8-monthly-meeting program, it is believed that an agency has been provided that is of great benefit to the individual engineer and to the Section. The extensive series of inspection trips previously mentioned as having been set up by the related activities committee of the power group has proved so popular that in some cases the demand for tickets has far exceeded the available accommodations. These trips have included, among others, those to newspaper plants, a brewery, the S. S. "Normandie," an airplane carrier of the U. S. Navy, General Electric Works at Schenectady, N. Y., the General Electric "House of Magic," Pennsylvania Railroad electrification, and the Richmond

## Membership—

Mr. Institute Member:

As of March 2 the number of applications received for admission to the Institute was 1,304 as compared with 1,095 of last year. This increase continuously attests to the effectiveness of your inviting to Institute membership those who you think worthy.

Very shortly now we will be asking you by letter to continue to help your Section membership committees in this way.

Everett S. Lee

Chairman National Membership Committee

station of the Philadelphia (Pa.) Electric Company.

When a charge has been necessary to cover inspection trip arrangements, the policy has been established of requiring payment of a higher fee by nonmembers wishing to take part. This practice has applied also to the registrants in the courses now being given. Perhaps here lies at least a partial answer to the oft encountered reactions to membership solicitation: "Why should I join the A.I.E.E.? I can attend the meetings anyhow and read the publication in the company office."

In drawing this picture of what has been accomplished under the group plan of operation in the New York Section it has been possible only to hint at one of the controlling factors to which success has been largely attributable—co-operation by committees, individuals, the utilities, the manufacturers, in fact, by all the interests involved. To the committeemen, the men who have carried the real burden, all credit is due. They have shown an interest and enthusiasm which speaks well for the future, and they have borne the headaches without a protest. The fund of talent and range of interests available to the New York Section, of course, places it in an enviable position for the carrying out of comprehensive activities; but the size of the Section also presents some apparently insurmountable difficulties to the accomplishment of certain desirable goals. General get-togethers of any large part of the membership are impractical. It is only through the contacts provided at meetings, on inspection trips, and in committee work that the members get to know many of their brother engineers who are not their immediate associates. It is therefore on these activities that the emphasis has been placed in group operation. The use that can be made in other Sections of the methods that have led to success in New York must be somewhat dependent on local conditions. It is hoped, however, that at least some of the ideas here touched upon may prove of value in building up a bigger and better A.I.E.E., an A.I.E.E. that really will help the individual engineer in many material ways.

## Tesla Coil to Be Exhibited at Engineers' Show

ANNUALLY, the senior engineers of Texas Technological College, Lubbock, sponsor an engineers' show consisting of all the principal attractions of the school together with any individual exhibits assembled by students. Each year, the senior electrical engineers offer the Tesla coil shown in the accompanying illustration as one of the principal attractions of the electrical engineering department, and, according to John L. King (Enrolled Student), manager of this year's show (April 17–18), it never ceases to be of interest. The coil is 9 feet high and is rated 10 kw; it is designed to discharge a 10 foot spark of about 3,000,000 volts at a frequency of 50,000 cycles per second. The spark shown in the illustration is limited to about 6 feet by the size of the room in which the coil is placed.

## A.S.A. Standards for Rotating Machinery

New and revised requirements for most of the rotating electrical machinery manufactured and used in the United States are now made available in a single volume, the "American Standards for Rotating Electrical Machinery," just published by the American Standards Association.

Standard requirements and specifications for electrical machinery, from the large central station generators and industrial and steel mill motors to the small motors used on household appliances, such as vacuum cleaners and electric fans, are included in the new publication. Synchronous, induction, and d-c machines, synchronous converters, and a-c and d-c fractional horsepower motors are covered.

With new material added by the American Standards Association's committee, the publication combines revisions of the material formerly published by the A.I.E.E. in 5 separate pamphlets (A.I.E.E. Standards 5, 7, 8, 9, 10) and those motor and generator standards of the National Electrical Manufacturers Association that are of general interest.

By specifying that a machine must conform to the American Standards, a buyer now can be relieved of worry about the details of design, unless his requirements are very special, because the American Standards establish the essential features. He can be sure that he is obtaining a machine of approximately the same characteristics to do a specific job, from any reputable manufacturer.

The N.E.M.A. rules which, together with the A.I.E.E. standards, form the basis for part of the new standards, deal particularly with manufacturing practice as it has grown up for various types of machines and include such standards as values for rating purposes, dimensions, and structural details.

The outstanding accomplishment of the A.I.E.E. standards has been the definition of the terms and conditions that characterize rating and performance. The line of demarcation has not been distinct, and with the growth and increased detail of both the A.I.E.E. and N.E.M.A. standards, this dividing line became less distinct. In the new standards, these 2 existing and overlapping sets of standards are combined to form one complete "common language" for rotating machinery.

Single copies of this standard pamphlet "Rotating Electrical Machinery," No. C-50, may be obtained either from the A.S.A. or from A.I.E.E. Headquarters, 33 West 39th Street, New York, N. Y., at $1.30 each, with the usual 50 per cent discount to A.I.E.E. members.

## Third Annual Report of E.C.P.D. Published

Recent publication of the third annual report of the Engineers' Council for Professional Development makes available to engineers and educators a record of the activities of this body. It provides authentic information on the organization, purposes, policies, personnel of the Council and the work of its 4 major committees on student selection and guidance, engineering schools, professional training, and professional recognition.

The 36 page annual report contains a list of the participating bodies and their representatives for 1935–36, the report of C. F. Hirshfeld, chairman of E.C.P.D. for 1935, committee reports, the charter and rules of procedure of E.C.P.D., the policies adopted by E.C.P.D. since its formation, a brief report on finances, and the committee personnel for 1935–36.

Chief interest attaches to the 4 committee reports. The report of the committee on student selection and guidance, of which R. L. Sackett, dean of the college of engineering, Pennsylvania State College, is chairman, deals principally with tests designed to supplement methods of selecting students for engineering colleges.

Plans for putting into effect its program of accrediting engineering schools are discussed in the report of the committee on engineering schools, of which Karl T. Compton, president, Massachusetts Institute of Technology, is chairman.

An appendix to the report of the committee on professional training, of which Robert I. Rees, assistant vice president, American Telephone and Telegraph Company, is chairman, contains an announcement of a selected bibliography of engineering subjects with samples from the civil engineering section, covering selected books on bridges, concrete, construction materials, foundations, highways, hydraulics, mechanics of materials, railroads, sewerage and sewage disposal. Other sections of the bibliography will cover mathematics, physics, chemistry, aeronautical engineering, chemical engineering, electrical engineering, industrial engineering, mechanical engineering, metallurgical engineering, and mining engineering.

A second appendix to this report presents a preliminary survey of university extension facilities, including a general description of the scope of the courses included in the survey and a list of the educational institutions giving these courses through classroom and correspondence study. A suggested operating program for the professional development of junior engineers comprises a third appendix to this report.

Among other subjects the report of the committee on professional recognition, of which C. N. Lauer, president, Philadelphia Gas Works, is chairman, deals with registration of engineers, and includes, as an appendix, a digest of the engineer registration laws in 35 states.

The Engineers' Council for Professional Development is a conference of engineering bodies organized to enhance the professional status of the engineer through the cooperative support of those national organizations directly representing the professional, educational, and legislative phases of an engineer's life. The participating bodies are American Society of Civil Engineers, American Institute of Mining and Metallurgical Engineers, The American Society of Mechanical Engineers, American Institute of Electrical Engineers, Society for the Promotion of Engineering Education, American Institute of Chemical Engineers, National Council of State Boards of Engineering Examiners.

Charles F. Scott, chairman, Connecticut State Board of Registration, is chairman of E.C.P.D., and George T. Seabury, secretary, American Society of Civil Engineers, is secretary. Copies of the third annual report may be obtained at nominal cost by addressing The Engineers' Council for Professional Development, 29 West 39th Street, New York, N. Y.

## Midwest Power Conference to Be Held April 20–23

The 1936 Midwest Power Engineering Conference will be held at the Palmer House, Chicago, Ill., April 20–23. Co-operating in this affair are the Chicago sections of several engineering societies, including the American Society of Civil Engineers, The American Society of Mechanical Engineers, the A.I.E.E., the Edison Electric Institute, National Safety Council, American Society of Refrigerating Engineers, and the Western Society of Engineers. Conference committee representatives of the A.I.E.E. Chicago Section are J. E. Kearns (A'07, M'21) and F. H. Lane (M'23).

It is expected that 35 papers will be presented at the 12 sessions scheduled. There will be exhibits of power equipment, supplies, and services by leading manufacturers.

Arrangements have been made for reduced railroad fares on the "receipt certificate plan" on tickets purchased April 16 to 22, good for a return ticket purchased not later than April 27 over the same route. All members of the participating societies who pay the membership registration fee of $1.00 at the power conference will be entitled to the reduced return fare. Members wishing to take advantage of this offer must have their certificates validated by G. E. Pfisterer, secretary of the conference, at registration headquarters on April 22 or 23.

**Mammoth Electric Sign.** A huge electric sign, representing a million dollar investment of the Wm. Wrigley Jr. Company, has been constructed on the east side of Times Square in New York, N. Y., from 44th to 45th Streets. It contains 1,084 feet of neon tubing, almost 70 miles of insulated wire, 29,508 lamp receptacles, and 8 tons of galvanized sheet metal, and has a total weight of 110 tons. It is said that the total connected electrical load is 700 kw. The sign depicts a variety of tropical fish.

## Engineering Foundation

### Platform Adopted

On June 14, 1935, The Engineering Foundation board adopted the following platform, which supersedes the platform of 1925. The new platform was approved by the board of trustees of Foundation on June 27, 1935, and during subsequent months has been approved by 4 Founder Societies.

PREAMBLE

The Engineering Foundation board has contemplated its prospects for usefulness to the profession of engineering and to mankind, together with its probable resources of men and money. Guided by experience in 20 years characterized by profound changes in science, engineering, economics, industry, and political organization; assisted by many expressed opinions of members of its Founder Societies and friends, and encouraged by commendations and additional gifts from its founder and other persons, the Foundation board, without limiting the discretionary power bestowed by the founder and the Founder Societies through its broad charter, expresses its general plan and policy for the near future in the following platform, which supersedes the platform of 1925.

GENERAL PLAN AND POLICY

1. The Engineering Foundation recognizes the responsibility of leadership placed upon it for attaining the objectives set forth in the deed of gift.

2. The Foundation will concern itself with human as well as technical aspects of engineering problems of wide interest. Activities which will have as their main objectives "the advancement of the profession of engineering," whether by research or other means, will be given preference.

3. The Foundation will initiate new projects or will select from time to time projects presented to it which are deemed most likely to attain its objectives.

4. In examination of proposals and in development of those selected the Foundation will seek the collaboration of members or committees of its Founder Societies especially conversant with the subject under consideration. It will also seek other counsel as needs arise.

5. It will assist in developing selected proposals into organized projects, and will choose a competent agency for the conduct of each project, when in approved form.

6. It will assist approved projects, according to the needs of each, by grants of money, by solicitation of contributions of money, services, and materials, and in other ways.

7. Responsibility for development and prosecution of each project shall rest upon the chosen agency, which agency shall have the largest practicable measure of freedom in carrying out the project.

8. The Foundation will require periodically an accounting for resources supplied for each project and acceptable reports of results.

9. Proposals recommended by its Founder Societies and of broad interest to the profession will be given preference.

10. The Foundation will endeavor within its sphere of influence to prevent conflict of research activities and such duplication as would be wasteful.

## American Engineering Council

### Rural Electrification

Rural electrification now has the support of legislation. The new act provides $42,000,000 per year for 10 years for the construction of transmission lines into rural areas and the construction of generating plants where an adequate supply of electricity is not available, or where it cannot be obtained at what are thought to be reasonable prices. However, present rural electrification commitments range between 5 and 6 million dollars for about 5,000 miles of transmission lines to take care of 17,500 farm families. Money for these extensions is loaned at 3 per cent for 20 years. With few exceptions, these new lines are interconnected with privately owned utilities for their supply of electricity. This trend, both in volume and in method, is following principles and recommendations earlier made by American Engineering Council committees and staff to the Rural Electrification Administration.

### Activities of National Resources Committee

The National Resources Committee, known originally as the National Planning Board, has been seeking legislation making possible the creation of a planned approach to the development of our natural, as well as human, resources. The hearings held before the Land Policy Committee of the House of Representatives were not friendly, perhaps because it is difficult to get congressmen to understand what is meant by "human resources." American Engineering Council has expressed itself as being in sympathy with some of the objectives of the National Resources Committee, particularly those objectives seeking to co-ordinate federal and state relations to such practical questions as water resources, flood control, and coordinated development of mineral resources.

One simple objective recommended by Council's committee on water resources, namely, to set up a board of water resources, which would serve as a clearing house for factual information on this subject, has had the approval of the members of the National Resources Committee and of its subcommittee on water resources. Similarly, the proposal for a basic mapping program has had the approval of the Water Resources Committee. In brief, it would seem possible to secure favorable consideration of a planned approach to the co-ordination of the orderly development of our "natural resources." When the word "natural" is supplanted by "national," and "human" as well as "material" resources are included, there apparently results a confusion of tongues.

# Letters to the Editor

**CONTRIBUTIONS to these columns are invited from Institute members and subscribers. They should be concise and may deal with technical papers, articles published in previous issues, or other subjects of some general interest and professional importance. ELECTRICAL ENGINEERING will endeavor to publish as many letters as possible, but of necessity reserves the right to publish them in whole or in part, or to reject them entirely.**

**ALL letters submitted for consideration should be the original typewritten copy, double spaced. Any illustrations submitted should be in duplicate, one copy to be an inked drawing but without lettering, and other to be lettered. Captions should be furnished for all illustrations.**

**STATEMENTS in these letters are expressly understood to be made by the writers; publication here in no wise constitutes endorsement or recognition by the American Institute of Electrical Engineers.**

## Voltage Regulation of Alternators

*To the Editor:*

Sections 121, 122, and 123 of the A.I.E.E. Proposed Test Code for Synchronous Machines gives a method of finding the voltage regulation and load field current of alternators. I should like to ask what features of the proposed A.I.E.E. method make it superior to the method referred to in textbooks by Lawrence ("Principles of Alternating Current Machinery") as the "general method" and by Bryant and Johnson ("Alternating Current Machinery") as "method *A*" which has a rational basis?

Although this so-called "general method" is theoretically correct only for cylindrical rotor machines the results obtained by it are in very close agreement with test results made on a wide classification of salient pole machines. The method also admits of a readily applied and accurate graphical solution which is of advantage to the designer and which will be illustrated.

The graphical solution requires the open-circuit, the short-circuit, and the full-load zero-power-factor saturation curves and the effective phase resistance. From point $A$ on the full-load zero-power-factor saturation curve (figure 1) lay off, on the normal voltage line, $AB$ equal to $OR$, the field current required to circulate full load current in the short-circuited armature. From $B$ draw a line parallel to the air gap saturation curve until it intersects the open-circuit saturation curve at $C$. From $C$ drop a perpendicular to the normal voltage line intersecting it at $D$. Then $CD$ is the full-load armature-reactance voltage in per cent of rated terminal voltage, and $DA$ is the full-load armature-demagnetizing effect of armature reaction in terms of field current. The illustration is carried out for the condition of generating full load at 0.8 inductive power factor. To vector $OE$, the rated terminal voltage at 0.8 power factor, add the full-load armature-resistance drop in per cent of normal voltage, equal to $EF$ and parallel to the voltage axis or current vector. From point $F$ add the full-load armature-reactance drop, equal to $CD$, in per cent of normal voltage, perpendicular to the voltage axis or current vector, obtaining $FG$. Generation of the resultant voltage, $OG$, requires from the open-circuit saturation curve, a field current $OH$. To $OH$ add the full-load armature demagnetizing effect $HI$, equal to $DA$, parallel to the generated voltage $OG$. Then $OI$, rotated to the field current axis, is the field current required to generate full load at normal voltage and 0.8 inductive power factor. The no-load voltage is $E_0$.

The ease of application of the foregoing graphical solution is apparent, and it is readily proved to be the "general method." Let $OE$, the rated terminal voltage, be the reference vector in figure 2, and draw $I_a$ lagging by the power factor angle $\theta_t$. To vector $OE$ add the full-load armature-resistance drop $EF$ parallel to the current vector $I_a$. From $F$ add the full-load armature-reactance drop $FG$. Generation of the resultant voltage $E_G$ requires, from the open-circuit saturation curve, a magnetomotive force $N(OH)$; $OH$ is the field current and $N$ the field turns per pole. The magnetomotive force $N(OH)$ and flux $\phi_R$ lead $E_G$ by 90 degrees. The armature magnetomotive force $N(HI)$ or $N(DA)$ is in phase with the armature current $I_a$. The field magnetomotive force must be strong enough to overcome the armature reaction magnetomotive force and also supply the useful magnetomotive force $N(OH)$. To obtain this field magnetomotive force subtract (vectorially) the armature magnetomotive force from the useful magnetomotive force $N(OH)$ giving $N(OI)$; $OI$, the field current necessary to generate full load at normal voltage, is $N(OI)$ divided by $N$.

To show that the graphical construction is the "general method" let the angle that $OG$ makes with $OH$ in the graphical construction be $\beta$. Since $HI$ is drawn parallel to $OG$, its angle with $OH$ projected is also $\beta$. In figure 2 $HI$ is drawn 180 degrees out of phase with $OI_a$, and $OI_a$ readily is seen to be at the angle $\beta$ with the projected $HO$ vector. Hence $HI$ is also at the angle

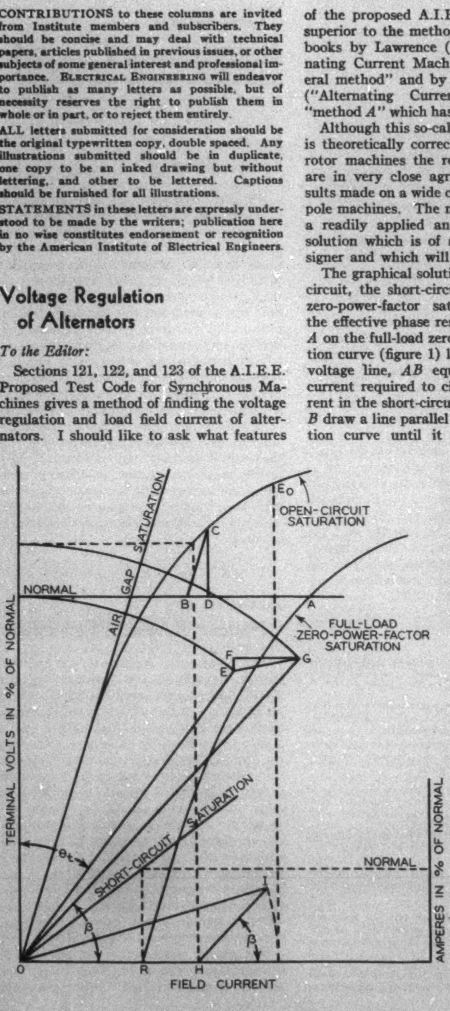
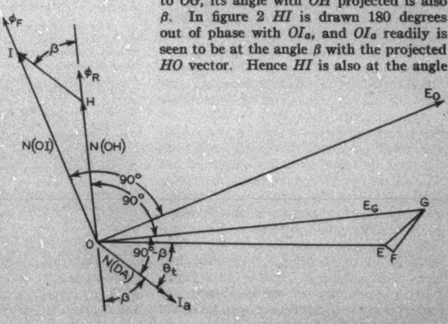


**Fig. 1 (left). Graphical method of determining voltage regulation of alternators**

**Fig. 2 (below). Vector diagram showing that method of figure 1 is equivalent to "general method"**



$\beta$ with the vector $OH$ projected and the 2 methods are identical.

Since this method is rational, exact, and readily applied, I would like to ask again: What features of the proposed A.I.E.E. method make it superior to this "general method"?

Very truly yours,

H. R. Reed (A'28, M'34)
Associate Professor of Electrical Engineering, Michigan College of Mining and Technology, Houghton

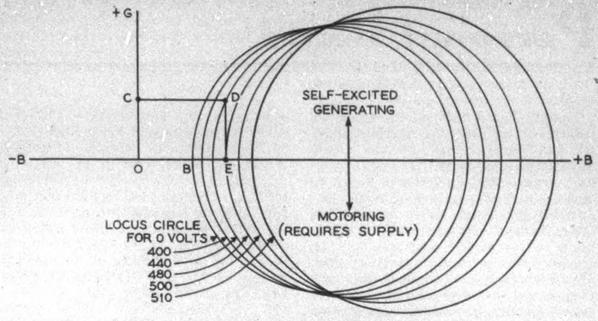


**Fig. 2. Admittance locus diagram for a self-excited capacitor generator**

## Mr. Canby's "Alma Mater"

*To the Editor:*

Some years ago Harold J. Laski wrote an article, "The Academic Mind." Appearing in *Harper's Magazine* for April 1929, the following may be seen:

> "Once practical men begin to meddle with universities, mediocrity within is given its opportunity. Orthodoxy becomes the ideal in any subject of social import. . . . What is the intellectual fashion of the moment is developed and cultivated at the expense of what is basic. The administrator becomes more important than the teacher, . . . The university, at the best, becomes a semitechnical school; and at the worst a graceful academy where the sons of practical men learn that modicum of cultivation which social success demands."

This is now made the more pertinent by the recent publication of Henry Seidel Canby's volume "Alma Mater." Reviews of this work can be seen in:

| | |
|---|---|
| *Saturday Review of Literature* | Feb. 22, 1936 |
| New York *Times* Book Review | Feb. 23, 1936 |
| New York *Herald Tribune* "Books" | Feb. 23, 1936 |

These furnish most interesting reading since each reviewer has been stimulated to incisive comments on education. One of them states that Mr. Canby's schooling seemed to align fairly well with the American notion that "a power trust is all right if run by the right people, but a 'brain trust' in government is contemptible upon any terms." The book itself is a recording, by a person of unimpeached intellectual and "success" attainments, that Liberal education in its heyday was a rather barren thing. As he looks back he finds true scholars rare, and the independent thinker—as Sumner—suspect by influential alumni. This is noted in spite of implicit resentment toward "hardboiled" science incapable of being bluffed.

I submit herewith that the urging toward social studies in engineering education can well bear scrutiny in the light of these matters. Particularly so as economics is to be fostered as a desirable in the training of "engineer $\alpha$," to say nothing of it being nominated as a vital principle to help "engineers $\beta$" and "$\gamma$" along.

Social scientists affect a view that physical science has produced a Frankensteinian monster from which the social studies alone are competent to save humanity. This in the face of social scientists lacking and needing a point of view relevant to all science and which a competent training in physical science alone seems able to give. The things of which Mr. Canby writes are the stuff of which the humanities are made and their present character is just about the same as was permitted in his day by economic circumstances and popular opinion.

Few engineers, I believe, look back on their professional schooling to see it, the sterile thing that Mr. Canby views at this distance. Nor can I believe that they must evaluate their teachers as he has his—like medieval monks doing office—in vicarious expiation for venal control groups. Remembering, however, that our business and management goadings are not vastly different from those stimulating society in his college and teaching days, it is well to consider how much of uncompromising logical process may be displaced by pseudo science before technical graduates are able to look back and see such as he has set forth.

Very truly yours,

J. Andrew Douglas (A'18, M'29)
313 McDonald Ave., Mobile, Alabama

## Equivalent Circuit of a Self-Excited Capacitor Generator

*To the Editor:*

I was very interested in the paper "Capacitive Excitation for Induction Generators" by Bassett and Potter, which was published in the May 1935 issue of Electrical Engineering (pages 540–5), and also in the discussion which has followed to date; it appears that this type of machine is still without any definite application.

Some years ago I constructed the following method of attack of this problem, which shows the minimum excitation capacitance and the regulation on any load, and also the maximum load capacitance at a glance.

In figure 1 are shown equivalent impedance and admittance diagrams of a self-excited capacitor generator, where

$L_L$ = load inductance in henrys
$R_L$ = load resistance in ohms
$C$ = capacitance in microfarads
$G_G$ = generator conductance in mhos
$B_L$ = load susceptance in mhos
$G_L$ = load conductance in mhos
$B_C$ = capacitive susceptance in mhos
$B_G$ = generator susceptance in mhos
$f$ = frequency in cycles per second

For stability, $B_C = B_G + B_L$ and $G_L = G_G$.

It will be obvious that the generator conductance and susceptance are a minimum at 0 volts and increase on account of the saturation of main and leakage flux paths with increasing voltage.

The admittance locus diagram shown in figure 2 is roughly similar to the current locus circle diagram and is plotted for one particular frequency, say 60 cycles. The usual construction for slip is in order, and the generator must be driven supersynchronously by that amount of slip for the load point considered. In figure 2, $Oc = G_L$ and $CD = B_C - B_L$. If the capacitive susceptance be larger than $OB$, the machines will excite on no load; hence full load voltage (for point $D$) = 440 volts, and no load voltage (point $E$) = 480 volts.

Very truly yours,

Reginald D. Ball (A'31)
English Electric Co., Bradford, Eng.

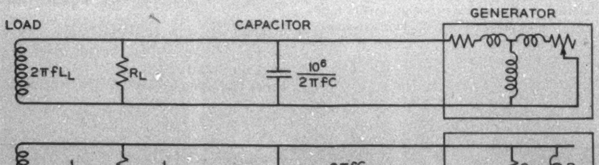


**Fig. 1. Equivalent impedance (upper) and admittance (lower) diagrams for a single phase capacitor generator (or for a single phase of a 3-phase star-connected capacitor generator**

# Personal Items

Francis Hodgkinson (A'02) consulting mechanical engineer, Westinghouse Electric and Manufacturing Company, South Philadelphia, Pa., recently retired from active service. Mr. Hodgkinson was born in London, England, June 16, 1867, and attended the Royal Naval School, New Cross, England. He received the honorary degree of mechanical engineer from the Stevens Institute of Technology in 1934. After having served an apprenticeship with Clayton and Shuttleworth, agricultural engineers, Lincoln, England, he became associated (1885) with C. A. Parsons in the early development of the reaction steam turbine. In 1890 he joined the Chilean Navy and served as engineer aboard a torpedo boat destroyer until the termination of the civil war in that country. During the period 1891–94 he served as assistant engineer at an electric lighting station in Lima, Peru, and as installation engineer for a mining company in Casapalca, Peru. In 1894 he rejoined C. A. Parsons and Company, Newcastle, England, as superintendent of construction. In 1896 when the late George Westinghouse (A'02) negotiated a license agreement with C. A. Parsons and Company, Mr. Hodgkinson became associated with the Westinghouse Machine Company. He was in charge of steam turbine construction until 1916 when he was made chief engineer of the Westinghouse Electric and Manufacturing Company. In 1926 he became consulting engineer for that company, and served in that capacity until the time of his retirement. He served on the Institute's committee on applications to the iron and steel industry, 1914–15, and on the power generation committee, 1924–28. He is a member of the Institution of Mechanical Engineers of Great Britain and The American Society of Mechanical Engineers.

R. E. Doherty (A'16, M'27) dean of the School of Engineering, Yale University, recently was elected president of the Carnegie Institute of Technology. Professor Doherty was born at Clay City, Ill., January 22, 1885. He received the degrees of bachelor of science in electrical engineering (1909), master of science (1921), and the honorary degree of master of arts from the University of Illinois, Union College, and Yale University, respectively. He was engaged by the General Electric Company, Schenectady, N. Y., in 1909, and during the period 1910–20 he was designing engineer for that company. In 1920 he became assistant to the late Dr. C. P. Steinmetz (A'90, M'91, F'12, and past-president) and continued to serve in that capacity until the death of Doctor Steinmetz in 1923. He was consulting engineer for the General Electric Company from 1923 until he became professor of electrical engineering at Yale University in 1931. He was appointed dean of the school of engineering in 1932. He served as a member of the Institute's education committee 1918–19 and 1926–28, and as chairman 1931–35. He was also a member of the committees on electrophysics (1924–26), power transmission and distribution (1928–29), and technical program (1931–33). During the period 1926–27 he served as chairman of the Schenectady Section of the Institute. Professor Doherty has contributed much to technical literature, and is the author of numerous papers presented to the Institute. He is a member of the Society for the Promotion of Engineering Education, Tau Beta Pi, Sigma Xi, Theta Delta Chi, and Eta Kappa Nu.

E. A. Loew (A'08, M'13) professor of electrical engineering, University of Washington, Seattle, recently was appointed dean of the college of engineering. Professor Loew graduated from the State Teachers College, Oshkosh, Wis., in 1901, and received the degrees of bachelor of science in electrical engineering and electrical engineer from the University of Wisconsin in 1906 and 1922, respectively. He accepted a position on the electrical engineering faculty of the University of Wisconsin in 1906 and remained there until he transferred to the University of Washington in 1909. During the period 1917–20 he secured leave of absence to serve as electrical engineer and superintendent of the American Nitrogen Products Company. He served later in the capacity of consulting engineer for the same company until 1928. He returned to the University of Washington in 1920 and has been professor of electrical engineering since 1923. He has contributed much to technical literature. Professor Loew served as member of the Institute's education committee 1916–17 and 1929–31, and of the power transmission committee 1926–27. He is a past-chairman of the Seattle section (1925–26), and was chairman of the 1935 Pacific Coast convention committee. He is a member of Tau Beta Pi and Sigma Xi.

David Sarnoff (M'23) president, Radio Corporation of America, New York, N. Y., recently was awarded the decoration of Officer of the Oaken Crown of the Grand Duchy of Luxembourg. The award was made by W. H. Hamilton, charge d'affaires and consul general of the Grand Duchy, at the command of H. R. H. the Grand Duchess Charlotte, "in recognition of his pioneering work and contribution to the radio art." The cross of chevalier of the Legion of Honor was awarded to Mr. Sarnoff by the French government in 1935.

L. W. Robert (A'31) former assistant secretary of the U.S. Treasury Department, is now with the Allied Chemical and Dye Corporation, New York, N. Y. He was born in Monticello, Ga., September 3, 1888, and received the degree of bachelor of science in civil engineering from the Georgia School of Technology in 1908. He received a degree in electrical engineering at the same institution the following year. During the period 1909–12 he was engineer for the consulting firm of P. A. Dallas, Atlanta, Ga. In 1912 he became a member of the firm of Dallas-Robert Company, and in 1917 he organized his own firm of Robert and Company, Inc., with headquarters at Atlanta. In 1933 he was appointed assistant secretary of the treasury in charge of public buildings. During the following year he was removed from building supervision to the Bureau of Engraving and Printing. He is a member of American Society of Civil Engineers and The American Society of Mechanical Engineers.

S. W. Greenland (A'11, M'17) general manager for the federal trustee of the St. Louis (Mo.) Public Service Company, recently was elected president of the Midwest Transit Association. Mr. Greenland received his formal engineering training at Pennsylvania State College (1896–99) and in 1902 he entered the construction department of the American Telephone and Telegraph Company, with headquarters at Pittsburgh, Pa. He was manager and engineer, Columbus (Miss.) Railway, Light and Power Company from 1907 until he moved to Indiana in 1911 to become general manager of the Fort Wayne and Northern Indiana Traction Company. In 1910 he served as president, Mississippi Electric Light Association and as a member of the executive committee of the National Electric Light Association. In 1916 he was president of the Indiana Electric Light Association. He became vice president and general manager, Indiana Service Corporation, Ft. Wayne, in 1921, and was associated with Newman Saunders and Company, Inc., St. Louis, from 1925 until he became general manager of the St. Louis Public Service Company in 1928.

C. E. Stryker (A'21, F'35) formerly chief engineer, Fansteel Products Company, Inc., North Chicago, Ill., is now with McKinsey, Wellington and Company, with offices at Chicago. Mr. Stryker received the degree of bachelor of science in electrical engineering (1917) and the degree of electrical engineer (1924) at the Armour Institute of Technology. For 2 years following his graduation he was employed as testing engineer, Commonwealth Edison Company, Chicago. In 1920 he became assistant professor of electrical engineering, Armour Institute of Technology, and at the same time served as electrical engineer for the Ozone Pure Airifier Company; later he served in the same capacity for the Underwriters' Laboratories. In 1923 he became affiliated with the Fansteel Products Company and served continuously, in several capacities, until his recent resignation. He is a member of the Society of Automotive Engineers.

L. T. Merwin (A'10, F'33) who has been vice president and general manager, Northwestern Electric Company, Portland, Ore., recently was elected president. Mr. Merwin was born at Plainfield, N. J., October 23, 1873, and received the degree of bachelor of science at the University of California in 1896. Following his graduation he was a teacher of mathematics and physics in California high schools until 1901. During the period 1901–06 he was employed in various capacities by the San Joaquin Lighting Corporation, San Francisco, Calif., and during the following year he was district manager for the Nevada-California Power Company, Goldfield, Nev. He was electrical engineer for the Goldfield Consolidated Mines Company from 1907 until he became affiliated with the Northwestern Electric Company in 1912. He has served that company successively as transmission engineer, operating engineer, general superintendent, assistant general manager, and vice president and general manager. In 1934 Mr. Merwin was president of the Northwest Electric Light and Power Association.

**H. M. Marsden** (A'31) former district engineer, Hartford Steam Boiler Inspection and Insurance Company, New York, N. Y., has been made assistant chief electrical engineer, with offices at Hartford, Conn. Mr. Marsden was employed by the General Electric Company, Schenectady, N. Y., in test and laboratory work in 1912. During the period 1916–19 he was assigned to the Bureau of Engineering, U.S. Navy, as assistant inspector of engineering material. In 1919 he established his own electrical contracting business, and in 1922 he became a member of the testing and laboratory staff of the Georgia Railway and Power Company, Atlanta. He became electrical inspector in the Cincinnati (Ohio) offices of the Hartford Steam Boiler Inspection and Insurance Company in 1923, and in 1930 he was transferred to the New York headquarters as district engineer.

**Edgar Kobak** (A'21, M'22) has resigned as vice president in charge of sales, National Broadcasting Company, New York, N. Y., to become vice president of Lord and Thomas, New York. Mr. Kobak attended the Georgia School of Technology and was employed by the Georgia Railway and Power Company, Atlanta, during the period 1912–16. In 1916 he became the Atlanta representative of *Electrical World*. In the same year he became assistant engineering editor, and in 1920 he was transferred to Chicago, Ill., as assistant western manager. He spent one year in St. Louis, Mo., in a similar capacity before he returned to the New York headquarters to become promotion manager, and later, vice president of the McGraw-Hill Publishing Company. He resigned his position with that company in 1934 to become affiliated with the National Broadcasting Company.

**H. P. Liversidge** (A'12, M'17) vice president and general manager, Philadelphia (Pa.) Electric Company, has been elected a director of that company. Mr. Liversidge received the degree of bachelor of science in electrical engineering at Drexel Institute in 1898, and has been associated with the Philadelphia Electric Company continuously since that time. He has been active in the Institute's affairs, and has served on the following technical committees: meetings and papers, 1920–21; power stations, 1918–24; electrical machinery, 1923–24; Edison Medal, 1927–29; code of principles of professional conduct, 1928–29. He was chairman of the Philadelphia Section of the Institute for the year 1916–17. He is a member of The American Society of Mechanical Engineers and the Illuminating Engineering Society.

**J. B. Swering** (A'35) who has been assistant chief electrical engineer, Hartford Steam Boiler Inspection and Insurance Company, Hartford, Conn., has been made chief electrical engineer. Mr. Swering graduated from South Dakota State College in 1909 with the degree of bachelor of science in electrical engineering. After a brief service in construction and maintenance work, he became field engineer for the C. W. Roland Company, Des Moines, Iowa. In 1916 he became test engineer for the Westinghouse Electric and Manufacturing Company, East Pittsburgh, Pa., and in 1922 he was made service manager in the Buffalo, N. Y., offices of that company. He accepted the position of assistant electrical engineer for the Hartford Steam Boiler Inspection and Insurance Company in 1923.

**L. D. Singleton** (A'19, M'26) formerly assistant chief electrical engineer, Braden Copper Company, New York, N. Y., is now electrical engineer for the Port of New York Authority. Mr. Singleton was engaged in electrical maintenance and contracting work during the period 1912–17. During the 2 following years he was employed as test engineer by the Westinghouse Electric and Manufacturing Company, East Pittsburgh, Pa., and in 1919 he accepted a position as generating station foreman for the Braden Copper Company, Rancagua, Chile. He held successively the positions of field electrical engineer and senior field electrical engineer before he was transferred to the New York offices as assistant chief electrical engineer of that company.

**G. A. Mills** (M'18) recently was elected president of the Kansas Electric Power Company, Lawrence, and the Missouri Gas and Electric Company, Lexington. Mr. Mills is a graduate of Iowa State College. He held the position of chief engineer of the Central and Southwest Utilities Corporation, Dallas, Texas, from 1926 until he moved to Michigan in 1932 as president of the Michigan Gas and Electric and Michigan Public Service Companies. In 1935 he became vice president of the Kansas and Missouri companies that now have made him president. Mr. Mills is the author of an Institute paper (1929) on "Interconnection in the Southwest." He is a charter member of the Dallas Section of the Institute and was its first chairman. A brief biographical sketch of Mr. Mills appeared in the January 1932 issue of ELECTRICAL ENGINEERING.

**A. D. Brown** (A'31) formerly district manager, Allis-Chalmers Manufacturing Company, Inc., Buffalo, N. Y., has been transferred to the Los Angeles (Calif.) offices of that company, where he will serve as manager. Mr. Brown graduated from Union College with the degree of bachelor of engineering in 1911. He was associated with the Aluminum Company of America, Pittsburgh, Pa., on various engineering projects, for a period of 3 years following his graduation. He then entered the employ of the Pittsburgh (Pa.) Transformer Company, and was retained as sales engineer for the Allis-Chalmers Manufacturing Company, Inc., when that company purchased the Pittsburgh Transformer Company in 1927.

**A. J. Beljavsky** (M'33) doctor of technical sciences, professor of electrical engineering of the Industrial College in Novocherkassk, U.S.S.R., recently has received 2 honors. First, the electrotechnical laboratory of his college has been named after him. Second, The Electrotechnical Association of Berlin, Germany (Elektrotechnische Verein) has awarded him a diploma in recognition of his "prominent services in the field of alternating current engineering and especially in the field of alternating current rectifying," and has designated him as a member-correspondent of the association (July 1, 1935).

**C. A. Faust** (A'35) who has been associate editor of *Transit Journal*, New York, N. Y., is now with the Ohio Brass Company, Mansfield. Mr. Faust received the degree of bachelor of science in electrical engineering at Iowa State College in 1927. He was engaged on the staff of the *Transit Journal* in the same year and subsequently served that organization in several capacities. He is a member of Eta Kappa Nu and active in that organization.

E. A. LOEW

FRANCIS HODGKINSON

R. E. DOHERTY

R. E. Hellmund (A'05, F'13, Lamme Medalist '29) chief engineer, Westinghouse Electric and Manufacturing Company, East Pittsburgh, Pa., has been appointed by the Institute's board of directors to serve as an alternate for one of the Institute's representatives upon the electrical standards committee, an appointment which automatically makes Mr. Hellmund an alternate upon the U.S. National Committee of the International Electrotechnical Commission.

H. A. Winne (A'16) former head of the steel mill section, General Electric Company, Schenectady, N. Y., recently was appointed manager of sales of the mining and steel mill section. Mr. Winne received the degree of electrical engineer at Syracuse University in 1910. He entered the employ of the General Electric Company as a student engineer in the testing department in the same year, and has served that company continuously in several capacities.

H. E. Farrer (A'21) assistant to the national secretary, and secretary of the A.I.E.E. standards committee, New York, N. Y., has been appointed by the Institute's board of directors to serve as an alternate for one of the Institute's representatives upon the electrical standards committee, an appointment which automatically makes Mr. Farrer an alternate upon the U.S. National Committee of the International Electrotechnical Commission.

Guglielmo Camilli (A'26, M'27) electrical engineer, General Electric Company, Pittsfield, Mass., recently was selected to receive one of the Charles A. Coffin Foundation awards for 1935. Mr. Camilli was cited for the award because of his contribution to the advancement in design of high-voltage apparatus. He is co-author of a paper "Surge Protectors for Current Transformers" which appeared in the March 1936 issue of Electrical Engineering.

C. E. Stephens (M'22, and past-director) vice president, Westinghouse Electric and Manufacturing Company, New York, N. Y., has been elected first vice president of the Electrical Association of New York, Inc. Mr. Stephens has been active on Institute committees, and is now serving as chairman of the code of principles of professional conduct committee, of which he has been a member since 1930. He was a director of the Institute 1928–33.

E. A. Crellin (A'13, F'28) assistant to the vice president, Pacific Gas and Electric Co., San Francisco, Calif., recently was elected president of the San Francisco Engineers' Club. During the period 1931–32 Mr. Crellin was chairman of the San Francisco Section of the Institute and a member of the national committee on power generation. He is also the author of papers presented to the Institute.

H. H. Cake (A'23, M'30) has resigned as sales engineer of the General Electric Supply Company at Los Angeles, Calif., to become associated with J. E. Haseltine Company, Portland, Ore.

W. I. Slichter (A'00, F'12, and national treasurer) professor of electrical engineering, Columbia University, New York, N. Y., has been nominated by the Institute's board of directors for re-election by the board of trustees of the United Engineering Trustees, Inc., as a representative of the A.I.E.E. upon The Engineering Foundation Board for the 4-year term beginning in October 1936.

H. P. Charlesworth (M'22, F'28, and past-president) assistant chief engineer of the American Telephone and Telegraph Company, New York, N. Y., has, in addition to his other Institute committee duties, been appointed by the A.I.E.E. board of directors to serve for a year as a member of the board of directors of the American Standards Association, filling a vacancy.

H. H. Barnes, Jr. (A'00, F'13) commercial vice president, General Electric Company, New York, N. Y., has been appointed by the Institute's board of directors to serve as an A.I.E.E. representative on the Hoover Medal Board of Award to fill the unexpired term, ending in October 1941, of Dr. E. W. Rice, Jr., deceased.

J. B. Whitehead (A'00, F'12, Life Member, and past-president) dean, school of engineering, The Johns Hopkins University, Baltimore, Md., has been appointed by the Institute's board of directors to serve for 1936 as an A.I.E.E. representative on the Council of the American Association for the Advancement of Science.

Vladimir Karapetoff (A'03, F'12, and Life Member) professor of electrical engineering, Cornell University, Ithaca, N. Y., has been appointed by the Institute's board of directors to serve for 1936 as an A.I.E.E. representative on the Council of the American Association for the Advancement of Science.

H. V. Putman (A'23, M'32) recently transferred to East Pittsburgh, Pa., as manager of the switchgear engineering department of the Westinghouse Electric and Manufacturing Company, has returned to Sharon, Pa., as manager of the transformer engineering department.

H. J. Chanon (A '33) highway-lighting engineer, General Electric Company, Cleveland, Ohio, recently was chosen to receive one of the Charles A. Coffin Foundation awards for 1935. This recognition was given for his development of a new incandescent-lamp highway-lighting system.

V. A. Shbals (A '35) district wire and cable specialist, General Electric Company, New York, N. Y., recently was cited for a Charles A. Coffin Foundation award for 1935, in recognition of meritorious service in the design, development, and application of oil filled cable.

E. W. Rockwell (A'21) electrical engineer, Metropolitan Water District of Southern California, Los Angeles, has been elected an officer of the Los Angeles Engineers' Club.

H. W. Crozier (A'03, M'12) consulting engineer, San Francisco, Calif., has received an appointment as project engineer of Lincoln County, district number one, with headquarters at Pioche, Nev. Mr. Crozier is a past-chairman of the San Francisco Section of the Institute.

Clarence Talsma (A '27) field engineer, General Electric Company, Omaha, Nebr., recently was selected to receive a Charles A. Coffin award for 1935 "in recognition of assistance rendered a public utility in restoring electric service after a severe flood."

P. M. Ross (A'34), formerly in the commercial engineering department of the Frigidaire Corporation, Dayton, Ohio, is now laboratory engineer for the insulator division of the Ohio Brass Company at Barberton.

D. S. Anderson (A'01) dean of the engineering school and acting president of Tulane University has been elected an honorary member of the Louisiana Engineering Society. He is a past-president of that society.

J. A. Osterlund (A'35) formerly with the sales department, International Business Machines Corporation, New York, N. Y., is now employed by A. E. Lee and Sons Company, San Juan, Puerto Rico.

C. N. Rice (A'28, M'36) has joined the staff of the Northern States Power Company at Eau Claire, Wis. Mr. Rice formerly was valuation engineer for Byllesby Management Corporation.

L. G. Gale (M'33) former chief electrical engineer, James Wilkinson and Company, Boston, Mass., is now sales engineer for the National Electric Products Corporation, with offices at Boston.

C. E. Plummer (A'33) formerly superintendent of electrical distribution for the Turlock (Calif.) Irrigation District, is now electrical engineer for the Modesto (Calif.) Irrigation District.

P. T. Filman (A'32) formerly employed by the Pennsylvania Power and Light Company, Warwick has been transferred to Mount Carmel in the generation department of that company.

D. A. Fleming (A'35) who has been plant electrician, Oklahoma Gas and Electric Company, Harrah, is now chief electrical operator of the Ponca City branch of that company.

C. D. Sasscer (A'27) formerly design engineer for the General Electric Company, Schenectady, N. Y., is now employed by the United States Engineer's Office, Quoddy, Me.

L. A. Whitsit (M'19) who has been employed by the U.S. Engineer's Office, Eastport, Me., is now with the Phoenix Utility Company, New York, N. Y.

John Baird (A'35) formerly assistant machinist, U.S. Fuel Company, Hiawatha, Utah, is now employed by the United States Bureau of Reclamation, Denver, Colo.

J. E. Dyer (A'30) who has been employed by the Sun Oil Company at Longview, Texas, has been transferred to the Dallas offices of that company.

**F. L. Ball** (A'22, M'27) vice president, Charles H. Tenney and Company, Boston, Mass., recently was elected president of the New England Gas Association.

**F. B. Menger** (A'34) who has been employed by the General Electric Company at Schenectady, N. Y., is now with the Armstrong Cork Company, Lancaster, Pa.

**C. V. Irish** (A'32) is now electrical design engineer with the Electro Dynamic Company branch of the Electric Boat Company, at Bayonne, N. J.

**J. A. Davis** (A'30) former manager, Ashland district, Virginia Electric and Power Company, has been transferred to the Richmond offices of that company.

**C. D. LaMoree** (A'25) manufacturer's agent, Los Angeles, Calif., has been elected an officer of the Los Angeles Engineers' Club.

**J. F. Murbach** (A'35) has accepted a position as research assistant for the Manufacturers Association, Inc., New York, N. Y.

# Obituary

**Edward A. Quinn** (M'15) former general superintendent, San Joaquin Light and Power Corporation, Fresno, Calif., died February 4, 1936. Mr. Quinn was born at Montreal, Canada, July 8, 1876. He attended St. Mary's College, Montreal, and Lewis College, Point Lewis, Quebec. In 1893 he entered the meter department of the Chicago (Ill.) Edison Company, and during 1894 he was employed by the Edison Light and Power Company, San Francisco, Calif. He was chief engineer of a small water works and generating plant at Santa Clara, Calif., from 1895 until he entered the employ of the Standard Electric Company of California in 1900. He assisted in the construction of the transmission system of that company, and later, in 1902, was made division superintendent. In 1904 Mr. Quinn became associated with the sales department of the Westinghhouse Electric and Manufacturing Company, San Francisco, and in 1907 he became general superintendent of the Nevada-California Power Company, Goldfield, Nev. He resigned from that position in 1909 to become sales engineer for the Allis-Chalmers Company, San Francisco. In 1914 he accepted the position of general superintendent of the San Joaquin Light and Power Corporation, and served in that capacity continuously until he retired in 1934.

**Kenneth Livermore Curtis** (A'05) consulting engineer, New York, N. Y., died February 18, 1936. Mr. Curtis was born at Augusta, Me., April 17, 1877, and received the degree of bachelor of science in electrical engineering at the University of Colorado in 1901. During the period 1901–03 he was employed in the testing department of the General Electric Company, Schenectady, N. Y. He became instructor in electrical engineering at Stanford University in 1903, and assistant professor of electrical engineering in 1906. In 1909 he established his own consulting practice in New York, and in the same year became chief engineer for the A. and J. M. Anderson Manufacturing Company, Boston, Mass. Mr. Curtis devoted much time to the development of control equipment, and was the designer of the steering gear systems of several naval ships.

**Harrison G. Folan** (A'23) assistant superintendent of distribution, New York and Queens Electric Light and Power Company, Flushing, N. Y., died June 29, 1935, according to word just received at Institute headquarters. Mr. Folan was born November 17, 1879, at Brooklyn, N. Y. A large part of his professional career was spent in transmission and distribution work, and his association with the New York and Queens Electric Light and Power Company began in 1913.

**Francis Rosbingrave Harvey** (A'21) engineer and manager, Wairere Electric Power Board, Pio, Pio, New Zealand, was killed by electric shock January 9, 1936, according to information recently received at Institute headquarters. Mr. Harvey was born at Brighton, England, November 9, 1884. He attended Holmwood College and Rochester Technical Institute in England, and later (1915) the Wellington (N. Z.) Technical School. After a 5 years' apprenticeship with the engineering firm of Aveling and Porter at Rochester, he entered the service of the Bexhill Municipal Electricity Department, where he served as accountant and as assistant engineer. In 1914, after a year as engineer for the New Zealand Shipping Company, he settled in New Zealand and became identified with some of the important electrical systems in that country.

**Kenneth Burr Jones** (A'16) vice president, Fruit-to-Lip Machine Company, Inc., New York, N. Y., died February 18, 1936. Mr. Jones was born July 14, 1893, at Brooklyn, N. Y., and graduated in 1916 from the Sheffield Scientific School of Yale University with the degree of bachelor of philosophy. Prior to his association with the Fruit-to-Lip Machine Company he was district manager for the C. H. Cowdrey Machine Works, New York.

**George W. Oliver** (A'35) substation inspector, Arkansas Power and Light Company, Pine Bluff, was killed instantly by electric shock January 7, 1936, according to information recently received at Institute headquarters. Mr. Oliver was born at Crewe, Va., December 27, 1897, and entered the employ of the Arkansas Power and Light Company in 1920. His service with that company was uninterrupted.

# Membership

## Recommended for Transfer

The board of examiners, at its meeting on March 25, 1936, recommended the following members for transfer to the grade of membership indicated. Any objection to these transfers should be filed at once with the national secretary.

**To Grade of Fellow**

Juhnke, P. B., chief load dispatcher, Commonwealth Edison Co., Chicago, Ill.
Lamar, R. W., V. P., and gen. mgr., Tennessee Public Service Co., Knoxville.
Tappan, F. G., prof. of E.E., acting dean, Coll. of Engg., Univ. of Oklahoma, Norman.
Wellwood, A. R., director, Electric Rate Survey Federal Pwr. Comm., Washington, D. C.

4 to Grade of Fellow

**To Grade of Member**

Bair, R. S., member of technical staff, Bell Tel. Labs., Inc., New York.
Beyer, J. W., member of technical staff, Bell Tel. Labs., Inc., New York.
Chesnut, R. W., telephone development engr., Bell Tel. Labs., Inc., New York.
Crane, R. E., member of technical staff (supervisor) Bell Tel. Labs., Inc., New York.
Egli, John, asst. supt., Allis-Chalmers Mfg. Co., Milwaukee, Wis.
Falkenstein, L. F., junior engr., N. Y. Edison Co., Inc., New York.
Fleshiem, R. S., mgr., elec. dept., Allis-Chalmers Mfg. Co., Milwaukee, Wis.
Flodin, C. R., Jr., division engr., Brooklyn Edison Co., Inc., Brooklyn, N. Y.
Grumbly, W. T., division engr., system engg. dept., N. Y. Edison Co., Inc., New York.
Harty, E. A., designing engr., Gen. Elec. Co., Lynn, Mass.
Kane, P. H., asst. supervisor, Brooklyn Edison Co., Inc., Brooklyn, N. Y.
Leinbach, A. R., power supply engr., N. Y. State Elec. & Gas Corp., Binghamton, N. Y.
Loveless, C. A., elec. sales engr., C. B. Fall Co., St. Louis, Mo.
Mayer, V. W., E.E., U.S. Navy Dept., c/o Federal S. B. & D. D. Co., Kearny, N. J.
McKeen, W. J., engr., inside construction, City Lt. Dept., Seattle, Wash.
Middleton, L. H., executive chief engr., The Electric Autolite Co., Toledo, O.
Neuman, J. J., chief elec. and research engr., Natl. Sugar Refining Co., Long Island City, N. Y.
Rosenberg, L. T., elec. machine designer, Allis-Chalmers Mfg. Co., Milwaukee, Wis.
Schonvizner, M. S., instructor in E.E., Carnegie Inst. of Tech., Pittsburgh, Pa.
Stanton, G. B., supervisor, Standards Section, Research Bureau, Brooklyn Edison Co., Inc., Brooklyn, N. Y.
Starr, E. W., asst. prof. of E.E., Cooper Union, New York.
Stratton, R. deF., substation supt., chief elec. engrs. branch, Dept. of Road Transport and Tramways, Sidney, N. S. W., Australia.
Waring, M. L., junior engr., System Planning Bureau, N. Y. Edison Co., Inc., New York.

23 to Grade of Member

## Applications for Election

Applications have been received at headquarters from the following candidates for election to membership in the Institute. If the applicant has applied for direct admission to a grade higher than Associate, the grade follows immediately after the name. Any member objecting to the election of any of these candidates should so inform the national secretary before April 30, 1936, or June 30, 1936, if the applicant resides outside of the United States or Canada.

Abt, C. F., New York Edison Co., Inc., N. Y.
Allen, L. W., Okonite Co., New York, N. Y.
Andrews, D. LeR., Idaho Pwr. Co., Boise.
Andridge, F. O., Graybar Elec. Co., Knoxville, Tenn.

**Armstrong**, C. V., Ingersoll Rand Co., New York, N. Y.
**Armstrong**, J. H., Williamsburg Pwr. Plant Corp. Brooklyn, N. Y.
**Ashla**, N. (Member), Westinghouse Elec. & Mfg. Co., Seattle, Wash.
**Bailey**, R. E., 1466 N. Willow St., Lake Forest, Ill.
**Baireuther**, E. J., 6733 W. Lloyd St., Wauwatosa, Wis.
**Banic**, J. M., Operadio Sound Equipment Co., Schiller Pk., Ill.
**Banks**, T. G., Jr., Oklahoma Theatre Supply, Oklahoma City.
**Barbier**, W. H., Philco Radio & Television Corp., Philadelphia, Pa.
**Bardsley**, R. V., 141–145 Railroad St., Woonsockett, R. I.
**Barnard**, E. H., Oilgear Co., Milwaukee, Wis.
**Barr**, W. G. A., Cemco Elec. Mfg. Co., Ltd., Vancouver, B. C., Can.
**Barrett**, E. J., Don Pedro Dam, La Grange, Calif.
**Barry**, J. C., Jr., Tennessee Pub. Serv. Co., Knoxville.
**Barth**, E. G., 516 Climax St., Pittsburgh, Pa.
**Bartlett**, J. T. (Member), Loeb & Shaw Inc., New York, N. Y.
**Bell**, J., B. C. Elec. Ry. Co., Ruskin, B. C., Can.
**Bell**, L. S., Gen. Elec. Co., Schenectady, N. Y.
**Bellows**, B. C. (Member), Bell Tel. Labs. Inc., New York, N. Y.
**Bennett**, G. H., Durham Pub. Serv. Co., N. C.
**Benson**, E. A., A. C. M. Co., Anaconda, Mont.
**Beren**, H. E., 2409 Park Row, Dallas, Texas.
**Berman**, S., Independent System, New York, N. Y.
**Berti**, R. J., Am. Dist. Tel. Co., Omaha, Neb.
**Best**, R. L., Monsanto Chem. Co., St. Louis, Mo.
**Bialkin**, B. L., 763 Home St., New York, N. Y.
**Billica**, H. J., Indiana Steel & Wire Co., Muncie, Ind.
**Bishop**, C. F., Philadelphia Elec. Co., Pa.
**Blackburn**, J. L., Westinghouse Elec. & Mfg. Co., E. Pittsburgh, Pa.
**Bobrove**, L., 6129 Delafield Ave., Riverdale, N. Y.
**Boskamp**, J. B., U.S. Army Motion Picture Serv., St. Louis, Mo.
**Bourassa**, W. O., Red River Pwr. Co., Grand Forks, N. D.
**Bovenzi**, A. L., Warren Bigelow Elec. Co., Worcester, Mass.
**Bowlus**, O. E., Emerson Elec. Mfg. Co., St. Louis, Mo.
**Boytano**, C. R., 274 Parkway, Chelsea, Mass.
**Bradley**, R. O., Whitehouse, Ohio.
**Brar**, S. S., Fresno State Coll., Clovis, Calif.
**Briganti**, C. L., % G. P. Bender, New York, N. Y.
**Brock**, P. J., Everhot Heater Co., Detroit, Mich.
**Brooks**, F. A., Bell Tel. Lab., Inc., New York, N. Y.
**Brown**, J. R., Hume & Rumble, Ltd., Vancouver, B. C., Can.
**Buckius**, O. E., Colgate, Palmolive, Peet Co., Berkeley, Calif.
**Buckley**, J. P., 2 Mott St., Worcester, Mass.
**Buggy**, R. V., Philco Radio Co., Philadelphia, Pa.
**Burns**, R. G., Allis-Chalmers Mfg. Co., Rochester, N. Y.
**Campbell**, A. S., Hotel St. George, Brooklyn, N. Y.
**Capello**, V. P., Whitney Mfg. Co., Hartford, Conn.
**Carpenter**, W. P., Gen. Elec. Co., Schenectady, N. Y.
**Carter**, I. R., Parkersburg Rig & Reel Co., Chase, Kans.
**Carter**, S. P., Nellis Coal Corp., W. Va.
**Cervenka**, F. J., Univ. of North Dakota, University Station.
**Chamberlin**, E. C., Fire Dept. New York, St. George, S. I., N. Y.
**Chase**, C. S., Rochester Telephone Corp., N. Y.
**Clark**, G. D. (Member), Gen. Motors, Warren, O.
**Clayton**, J. P. (Fellow), Commonwealth Edison Co., Chicago, Ill.
**Cohen**, I. W., 1602 W. 10th St., Brooklyn, N. Y.
**Colon**, E. R., New York Edison Co., Inc., N. Y.
**Como**, C., Brooklyn Edison Co., N. Y.
**Compton**, R. D., Natl. Broadcasting Co., New York, N. Y.
**Conner**, W. B., Lyndonville, Vt.
**Constantine**, P. M., 17 Liberty St., W. H., Newburgh, N. Y.
**Cooper**, W. E., Saguenay Pwr. Co., Ltd., Arvida, P. Q., Can.
**Cox**, W. W. Jr., Utah Pwr. & Lt. Co., Salt Lake City.
**Crabtree**, J. W., Tennessee Pub. Serv. Co., Knoxville.
**Creasy**, R. V., Newport News Shipbldg. & Drydock Co., Va.
**D'Alessandro**, A., Earth Testing Lab., U.S.B.R., Lovelock, Nev.
**Dameron**, E. C. (Member), Durham Pub. Serv. Co., N. C.
**Davenport**, L. B., Los Angeles Gas & Elec. Corp., Calif.
**David**, A. L., Gulf States Utilities Co., Navasota, Texas.
**David**, LeR., Pure Oil Co., Tulsa, Okla.
**Decker**, C. M., 245 Maple Pl., Minneola, N. Y.
**DeLanty**, L. J., Sperry Products Inc., Brooklyn, N. Y.
**DeSellem**, G. W. (Member), Westinghouse Elec. & Mfg. Co., Seattle, Wash.
**Dillman**, C. LeR., Box 955, Burns, Ore.
**Dolnick**, A., 1222 Gilsey Ave., Cincinnati, Ohio.
**Dunlap**, L. J., Westinghouse Elec. & Mfg. Co, Chicago, Ill.
**Dyer**, C. E., Midland Counties Pub. Serv. Corp., Santa Maria, Calif.
**Eckardt**, W. C. Jr., Abrasive Co., Philadelphia, Pa.
**Ego**, R. W., Lisbon, N. D.
**Ehrich**, H. E., Bell Tel. Labs. Inc., New York, N. Y.
**Ekstrand**, S. O., Bell Tel. Labs., Inc., New York, N. Y.
**Elderkin**, R. A., Leland Elec. Co., Canada Ltd., Toronto, Ont., Can.
**Eng**, W. B., 831 So. Rogers Ave., Okmulgee, Okla.
**Ernst**, M. L., Detroit Edison Co., Mich.
**Evans**, J. C., Wagner Elec. Corp., St. Louis, Mo.
**Everson**, J. K., 417 Spring Ave., Sioux Falls, S. D.
**Ewalt**, G. L., Jr., Cons. Gas Elec. Lt. & Pwr. Co., Baltimore, Md.
**Fairly**, R. F., Southwestern Associated Tel. Co., Lubbock, Texas.
**Fanley**, E. J., 148 E. State St., Columbus, O.
**Farison**, H. C., 528 N. College, Fayetteville, Ark.
**Fekete**, R., Gen. Elec. Co., Bridgeport, Conn.
**Fellner**, H. G., 1309 Lebanon Ave., Belleville, Ill.
**Finneburgh**, L. H., Jr., 12053 Lake Ave., Cleveland, Ohio.
**Fish**, D. B., Golden State Co. Ltd., San Francisco, Calif.
**Fish**, M. R., Pacific Tel. & Tel. Co., Tacoma, Wash.
**Fleischer**, H. E., New York Tel. Co., N. Y.
**Foster**, L. W., Gen. Elec. Co., Pittsfield, Mass.
**Frank**, L. C. (Member), Continental Motors Corp. Muskegon, Mich.
**Franke**, H. C., Bell Tel. Lab. Inc., New York, N. Y.
**Gallaher**, B. M., Tennessee Public Serv. Co., Knoxville.
**Gartin**, J. W., John A. Manning Paper Co., Troy, N. Y.
**Gaylord**, S. B., Western Pub. Serv. Co., Oshkosh, Neb.
**Glasser**, J., F. W. Sickles Co., Springfield, Mass.
**Glentzer**, K. V., Illinois Bell Tel. Co., Chicago.
**Gould**, K. E., Bell Tel. Lab., Inc., New York, N. Y.
**Graham**, C. H., Tennessee Valley Authority Knoxville.
**Grassmann**, W. J., New York Tel. Co., N. Y.
**Gray**, J. W., Univ. of Washington, Seattle.
**Grew**, L. B. (Member), So. New England Tel. Co., New Haven, Conn.
**Groendyke**, A., RCA Victor Co., Camden, N. J.
**Guignon**, J. E., Wagner Elec. Corp., St. Louis, Mo.
**Hackett**, C. S., Gen. Elec. Co., Schenectady, N. Y.
**Hall**, W. E., Westinghouse Elec. & Mfg. Co., Sharon, Pa.
**Harper**, R. L., Allen Bradley Co., Milwaukee, Wis.
**Harper**, S., 81 West 134 St., New York, N. Y.
**Harrison**, W. (Fellow), Gen. Elec. Co., Cleveland, Ohio.
**Hayden**, V. H., Gibson Elec. Co., Pittsburgh, Pa.
**Hermans**, C. E., Reed & Prince Mfg. Co., Worcester, Mass.
**Hernick**, P. W., Crown, Cork & Seal Co., Baltimore, Md.
**Hertner**, G. DeW., Hertner Elec. Co., Cleveland, Ohio.
**Higdon**, T. L., Federal Warehouse Washington, D. C.
**Higgins**, L. F., Illinois Bell Tel. Co., Chicago.
**Higley**, J. B., 311—5th St., Calexico, Calif.
**Hitchcock**, C. H., Allen Bradley Co., Milwaukee, Wis.
**Hobley**, H. R. B., Ford Motor Co., Dearborn, Mich.
**Hobson**, J. E., Earlham Coll., Richmond, Ind.
**Hodkins**, H. B., Westinghouse Elec. & Mfg. Co., Spokane, Wash.
**Holmes**, J. A., 714 S. E. 35 Ave., Portland, Ore.
**Hopkins**, E. J., RCA Radiotron Inc., Harrison, N. J.
**Howard**, I. T., P.O. Box 152, Wanchese, N. C.
**Howell**, R. L. (Member), J. D. Lanham Co., Greenwood, Miss.
**Howes**, J. T., 400 N. 11 St., Clinton, Iowa.
**Hubbard**, C. LaM., Houston Ltg. & Pwr. Co., Texas.
**Hubler**, N. W., Victor RCA., Camden, N. J.
**James**, W. G. (Member), Westinghouse Elec. & Mfg. Co., Sharon, Pa.
**Johnson**, J. A., Jr., N. Y. Pwr. & Lt. Corp., Albany, N. Y.
**Johnson**, J. S., Weston Elec. Instrument Corp., Newark, N. J.
**Johnson**, W. E., Turlock Irrigation Dist., Calif.
**Jones**, W. L., Standard Oil Co., Sugar Creek, Mo.
**Juckett**, W. B., Metropolitan Water Dist. of So. Calif., Berdoo, Calif.
**Kannenberg**, W. F. (Member), Bell Tel. Lab. Inc. New York, N. Y.
**Kaylor**, R. L. (Member), Bell Tel. Lab. Inc., New York, N. Y.
**Kirkman**, K., Baltimore Gas & Elec. Co., Md.
**Kohlerman**, F. L., Jr., Locke Insulator Corp., Baltimore, Md.
**Kohlroser**, V., Iron, Minn.
**Kurtz**, J. R., Elec. Serv. Supplies, Philadelphia, Pa.
**Kusich**, E. A., Ray Oil Burner Co., San Francisco, Calif.
**Lackland**, R. E. (Member), Am. Tel. & Tel. Co., New York, N. Y.
**Lambert**, E. G., Pacific Gas & Elec. Co., Oakland, Calif.
**Latwaitis**, W. W., Am. Tel. & Tel. Co., New York, N. Y.
**Leahy**, W. J., Jr., 58 Haigh Ave., Schenectady N. Y.
**Lear**, W. H. (Member), Am. Tel. & Tel. Co., New York, N. Y.
**Licandro**, J., Specialty Serv. Corp., Brooklyn, N. Y.
**Lockrow**, L. L., Bell Tel. Lab. Inc., New York, N. Y.
**Madsen**, H. C., Philco Radio & Television Corp., Philadelphia, Pa.
**Magnell**, A. A., Brooklyn Edison Co., N. Y.
**Mahoney**, J. A. (Member), Bell Tel. Lab., Inc., New York, N. Y.
**Manheimer**, D. I., 302 Marine Ave., Brooklyn, N. Y.
**Mars**, N., 1351 N. Tuxedo St., Indianapolis, Ind.
**Martin**, R. P., Jr. (Member), Bell Tel. Labs. Inc., New York, N. Y.
**Mau**, W. R. H., Jr., Houston Armature Works, No. 4, Texas.
**McCoin**, B. H., Tennessee Pub. Serv. Co., Knoxville.
**McEver**, R. W., Tennessee Pub. Serv. Co., Knoxville.
**McGeachie**, J. B., 27 Willcocks St., Toronto, Ont., Can.
**McGill**, T. A., Mid-West Dynamometer & Engg. Co., Chicago, Ill.
**McKibben**, G. M., Black Butte Rt., Cottage Grove, Ore.
**McLaughlin**, H. R., Remler Radio Co., San Francisco, Calif.
**McMenamin**, J. C., Jr., Gen. Elec. Co., West Lynn, Mass.
**McNeal**, J. D. W., Maryland Amplifier Co., Baltimore.
**McNutt**, W. K., 424 Hubert Ave., Springfield, Ohio.
**Messina**, J., 20 Squire Rd., Revere, Mass.
**Meyer**, W. W., Honold LePage Inc., Sheboygan, Wis.
**Miller**, H. C., Jr., Cons. Gas & Elec. Co., Baltimore, Md.
**Miller**, R. H., Underwood Elliott Fisher Co., Hartford, Conn.
**Milusich**, A. A., N. Y. Steam Corp., New York, N. Y.
**Mohler**, V. E., 30 N. Angelus, Memphis, Tenn.
**Moravek**, J. L., Crown Cork & Seal Co., Baltimore, Md.
**Morris**, W. D., Louisiana State Univ., Baton Rouge.
**Morrisey**, J. W., 429 N. Spring Ave., La Grange, Ill.
**Mulborn**, A. W., U.S. Dept. of Labor, San Francisco, Calif.
**Munro**, D. L., Wheeler Reflector Co., Boston, Mass.
**Munroe**, D. J., Liberty Mutual Insurance Co., Chicago, Ill.
**Napolitano**, A., Box 244, White River Junction, Vt.
**Nelson**, W. W., Electrical Equipment Co., Inc., Richmond, Va.
**Nervegna**, L., New York Edison Co. Inc., N. Y.
**Nickel**, W. F., 106 E. 41 St., New York, N. Y.
**Nickerson**, T. D., Scott Co., Oakland, Calif.
**Nielsen**, C. W., Tungsol Radio Corp., Newark, N. J.
**Nims**, R. L., Crocker-Wheeler Elec. Mfg. Co., Ampere, N. J.
**Noble**, E. T., Crosley Radio Corp., Kokomo, Ind.
**O'Brien**, J. J., 1122 Union St., Alameda, Calif.
**O'Brien**, M. P., Globe Wireless Ltd., San Francisco, Calif.
**O'Connor**, W. H., Jr., Bethlehem Steel Co., Sparrows Point, Md.
**O'Fiel**, J. C. D., Jr., 1214 Chartres St., Houston, Texas.
**Oliver**, F. S., Doble Engg. Co., Medford Hillside, Mass.
**Opdenweyer**, A. E., Portland Gen. Elec. Co., Hillsboro, Ore.
**Osis**, J. F., Michigan Bell Tel. Co., Detroit.
**Otteson**, W. I., Gibbs & Hill, New York, N. Y.
**Overmiller**, C. M. (Member), Am. Tel. & Tel. Co., New York, N. Y.
**Owen**, H. E., Technical High School, Buffalo, N. Y.
**Palm**, J. F., 1413 Neva Rd., Antigo, Wis.
**Pascher**, J. J., Gen. Elec. Co., New York, N. Y.
**Pearson**, S. J., Portland Gen. Elec. Co., Ore.
**Peeples**, E. E., Florida Pwr. & Lt. Co., West Palm Beach.
**Perkins**, J. R., Jr., Gen. Elec. Co., Schenectady, N. Y.
**Petersen**, H. O., Federal Shipbldg. & Drydock Co., Kearney, N. J.
**Petrasek**, W. A., Diehl Mfg. Co., Elizabethport, N. J.
**Pfeiffer**, F. R., Tung Sol Lamp Works, Newark, N. J.
**Pilch**, E., Emerson Radio & Television Corp., New York, N. Y.
**Pilione**, S. E., N. J. Bell Tel. Co., Newark, N. J.
**Piranian**, E. V., O'Connor & Piranian Engg. & Contracting Co., Philadelphia, Pa.
**Plummer**, R. W., Norwood, N. Y.
**Press**, M. M., 3244 Polk St., Chicago, Ill.
**Priday**, G. L., Gen. Elec. Co., Cleveland, O.
**Prince**, F. C., Tennessee Pub. Serv. Co., Knoxville.
**Princi**, M. A., Gen. Elec. Co., West Lynn, Mass.
**Pritchard**, G., New York Edison Co., Inc., New York.
**Profitt**, A. H., Tennessee Pub. Serv. Co., Knoxville.
**Pullen**, W. S., Jr., Gen. Elec. Co., Schenectady, N. Y.
**Rader**, I. A., Canadian Gen. Elec. Co., Vancouver, B. C., Can.
**Ramsay**, J. E., Geophysical Service Inc., Dallas, Texas.
**Ratica**, P. P., Bureau of Water, City of Pittsburgh, Pa.
**Rehwald**, E. A., John Deere Tractor Co., Waterloo, Iowa.
**Reilly**, F. W. (Member), G. & N. Engg. Co., Boston, Mass.
**Riefle**, J. H., Jr., Cons. Gas Elec. Lt. & Pwr. Co., Baltimore, Md.
**Rile**, J. C., Bell Tel. Labs. Inc., New York, N. Y.
**Rittenhouse**, J. F., Carlile & Doughty Inc., Conshohocken, Pa.
**Robey**, H. D., Robey Mfg. Co., E. Lansing, Mich.

Robinson, A. W., Jr., Southern Elec. Serv. Co., Greensboro, N. C.
Robinson, E. H., Greenfield Center, Saratoga Co., N. Y.
Rogers, J. R. (Member), Terre Haute Paper Co., Ind.
Rutter, C. M., Jr., Newport News Shipbldg. & Dry Dock Co., Va.
Ryder, A. J., No. 294, Sag Harbor, N. Y.
Saile, O. W., Gen. Elec. Co., Schenectady, N. Y.
Schechtman, J. M., Los Angeles Bureau of Pwr. & Lt., Calif.
Schwartz, S., Philco Radio & Tel. Corp., Philadelphia, Pa.
Sedlacek, W. C., Collins Radio Co., Cedar Rapids, Iowa.
Seewald, E. C., 617—21st St., N. W., Washington, D. C.
Shackford, C. C., John A. Roebling's Sons Co., Trenton, N. J.
Shaker, L. A., Darcey Transportation Co., Waterbury, Conn.
Shrader, L. C., Sr., Duncan Elec. Co., Lafayette, Ind.
Siegelin, W. G., State Line Gen. Corp., Hammond, Ind.
Simmerer, E. R., Northwest Baker Ice Machine Co., Seattle, Wash.
Sivells, J. C., Washington Univ., St. Louis, Mo.
Skok, S., Jr., 2470 E. 21st St., Brooklyn, N. Y.
Smith, R. H. (Member), Reliance Elec. & Engr. Co., Cleveland, Ohio.
Smith, S. B., Bd. of Transportation, New York, N. Y.
Sohnle, G. F., Bell Tel. Co., Inc., New York, N. Y.
Soley, W. A., Jr., Gen. Elec. Co., Bridgeport, Conn.
Speakman, L. F., Gulf Refining Co., Berwyn, Pa.
Spellman, F. C., 432 Prospect Pl., Brooklyn, N. Y.
Spohn, G. A., Gen. Machinery Corp., Hamilton, Ohio.
Sprole, R. R., Cornell Univ., Ithaca, N. Y.
Sprowls, P. H., Gulf Refining Co., Louisville, Ky.
Spruill, S. O., Tenn. Valley Authority, Florence, Ala.
Staller, J. R., Works Progress Administration, Schuylkill Haven, Pa.
Stancliff, G. L., Jr., Goodyear Tire & Rubber Co., Los Angeles, Calif.
Stanself, F. R., Bell Tel. Labs. Inc., Whippany, N. J.
Stoelting, H. O., Mission House Coll., Plymouth, Wis.
Stoner, S. C., 318—21st Ave., Altoona, Pa.
Stover, A. R., Kelvinator Corp., Chicago, Ill.
Street, H. V., Fla. Pwr. & Lt. Co., Miami, Fla.
Strickland, J. J., Jr. (Member), Durham Pub. Serv. Co., N. C.
Tavidian, E., F. W. Sickles Co., Springfield, Mass.
Testa, A., 326 Erin St., Vineland, N. J.
Thornton, J. R., Continental Can Co., San Jose, Calif.
Tietze, M. W., Harnischfeger Corp., Milwaukee, Wis.
Tomey, L. R., Emerson Elec. Mfg. Co., St. Louis, Mo.
Toomey, R. E., Carnegie Ill. Steel Corp., Homestead, Pa.
Towne, R. M., 2101 North Fife St., Tacoma, Wash.
Townes, W. A., 98 Kendall St., Boston, Mass.
Townley, J. G., Works Progress Administration, Ronceverte, W. Va.
Trembath, F., Westinghouse Elec. & Mfg. Co., Sharon, Pa.
Trice, T. W., Cons. Gas Elec. Lt. & Pwr. Co., Baltimore, Md.
Trifari, F. R., 2929 W. 16th St., Brooklyn, N. Y.
Troyak, G. E., Gen. Elec. Co., Schenectady, N. Y.
Tuite, J. M., Revere Copper & Brass Inc., Rome, N. Y.
Umphrey, D. M., Route No. 1, Eugene, Ore.
Vardon, E. C., Weston Elec. Instrument Co., Newark, N. J.
Vavra, S., Lankin, N. D.
Walkonen, T. K., Brooklyn Edison Co., Inc., N. Y.
Wallace, J. D., Topeka & Santa Fe Railway Co., Kansas.
Wallace, S. J., American Can Co., Vancouver, B. C., Can.
Wallis, D. E., New York Tel. Co., Mt. Vernon, N. Y.
Walsh, F. R., 273 Etna St., Brooklyn, N. Y.
Walstra, W. G., Idaho Pwr. Co., Boise.
Ware, H. S., Kelly-Koett Mfg. Co., Covington, Ky.
Warner, C. W., Cutler Hammer Inc., Milwaukee, Wis.
Watkins, W. W., Jones & Laughlin Steel Corp., Pittsburgh, Pa.
Weber, L. J., Muzak Corp. of Ohio, Lakewood, O.
Welch, A. U., Jr., Gen. Elec. Co., Pittsfield, Mass.
Wellauer, E. J., Falk Corp., Milwaukee, Wis.
West, R. J., Burlec Ltd., Toronto, Ont., Can.
White, C. F., 3026 Belmont Ave., Fresno, Calif.
Whitney, G. W., Stamford Gas & Elec. Co., Conn.
Whittington, J. W., Electrical Testing Labs., New York, N. Y.
Wit, S., RCA Mfg. Co., Inc., Camden, N. J.
Woo, A. S., Allis-Chalmers Mfg. Co., Milwaukee, Wis.
Wood, E. F. (Member), 415 Ralph St., Elmira, N. Y.
Wood, J. A. (Member), Am. Tel. & Tel. Co., New York, N. Y.
Yeranian, S., RCA Mfg. Co., Allston, Mass.
Zuske, H. J., Leece Neville Co., Cleveland, Ohio.

305 Domestic

**Foreign**

Epstein, G. L., Inst. of Communication, Moscow, U.S.S.R.
Leal, A. H., Rio de Janeiro Tramay, Brazil.
Lyman, V. A. (Member), Box 735, Balboa, Canal Zone.
Mongon, J. E., General Electrica Espanola, S.A., Bilbao, Spain.
Rodriquez, A. F., Cia de Tranvias Luz y Fuerza Montriz de Monterrey, Mexico.
Sanchez, H. M., 12 de Diegos Ave., Santurce, P. R.
Satoh, I., Ministry of Communications, Tokio, Japan.
Sitarma, M. R., c/o M. RamaRao, "Bloomfield" Mysore, India.
Sprenger, H., China Scientific Instrument Co., Shanghai, China.
Stoner, E. C., Jr. (Member), Cia Peruana de Telefonos Ltd., Lima, Peru.
Young, A. H., Shanghai Pwr. Co., China.

11 Foreign

## Addresses Wanted

A list of members whose mail has been returned by the postal authorities is given below, with the addresses as they now appear on the Institute record. Any member knowing of corrections to these addresses will kindly communicate them at once to the office of the secretary at 33 West 39th St., New York, N. Y.

Basinger, C. B., 749 Madison Ave., York, Pa.
Beaumont, L., Box 404, Shanghai, China.
Blanc, Victor, 153 Boulevard Lefebvre, Paris, France.
Daeley, Richard L., 1475 Pacific St., St. Paul, Minn.
DeKeyser, Jacques F., 37-53—78th St., Jackson Heights, N. Y.
Huang, Pienchun, Schillerstr 57, Berlin, Germany.
Johnson, James W., 3506—16th St., N. W., Washington, D. C.
Jones, Robert W., 565 Thompson Ave., Donora, Pa.
Meltvedt, Henry, 742 S. Douglas, Springfield, Mo.
Miyamoto, Tatsuo Charles, 517 M St., Sacramento, Calif.
Murray, Forrest H., 5530 Dorchester Ave., Chicago, Ill.
Patel, Ishvarlal B., 5 Second Carpenters St., Bombay, 4, India.
Ritter, Edward A., 40 Lexington St., Hamden, Conn.
Roberts, Fred A., 1528 Locust St., St. Louis, Mo.
Soskin, Samuel B., 1141 S. Central Park, Chicago, Ill.
Williams, Thomas J. C., 827 S. 48th St., Philadelphia, Pa.

16 Addresses Wanted

# Engineering Literature

## New Books in the Societies Library

Among the new books received at the Engineering Societies Library, New York, recently, are the following which have been selected because of their possible interest to the electrical engineer. Unless otherwise specified, books listed have been presented gratis by the publishers. The Institute assumes no responsibility for statements made in the following outlines, information for which is taken from the preface of the book in question.

GRAPHIC COURSE of PATENTABLE INVENTIONS. By H. A. Toulmin, Jr. N. Y., D. Van Nostrand Co., 1935. 40 p., tables, 9x6 in., paper, $1.00. The procedure to be followed in caring for a patentable invention is explained in this pamphlet, intricate steps being made clear by use of charts.

GRAPHICAL SOLUTIONS. By C. O. Mackey. N. Y., John Wiley & Sons, 1936. 130 p., illus., 9x6 in., cloth, $2.50. An elementary course in methods for the graphical and mechanical solutions of equations, discussing stationary adjacent scales, sliding scales, network charts, and alignment charts.

### Engineering Societies Library

29 West 39th Street, New York, N. Y.

MAINTAINED as a public reference library of engineering and the allied sciences, this library is a cooperative activity of the national societies of civil, electrical, mechanical, and mining engineers.

Resources of the library are available also to those unable to visit it in person. Lists of references, copies or translation of articles, and similar assistance may be obtained upon written application, subject only to charges sufficient to cover the cost of the work required.

A collection of modern technical books is available to any member residing in North America at a rental rate of five cents per day per volume, plus transportation charges.

Many other services are obtainable and an inquiry to the director of the library will bring information concerning them.

GREAT BRITAIN. DEPT. of SCIENTIFIC and INDUSTRIAL RESEARCH. REPORT for the YEAR 1934–1935. Lond., His Majesty's Stationery Office, 1935. 185 p., tables, 10x6 in., paper, 3s. (Obtainable from British Library of Information, N. Y., $0.95.) A survey of current research in all branches of science and industry, and of the latest results, to which directories of research organizations and lists of recent publications are appended.

MANUAL of FOREIGN PATENTS. By B. Severance. Washington, D. C., Patent Office Society, 1935. 161 p., 9x6 in., paper, $1.00. Lists patents and patent publications issued by foreign governments with descriptions of their contents, to which a glossary of foreign patent terms and a price list of publications are appended.

INDEX to A.S.T.M. STANDARDS and TENTATIVE STANDARDS, January 1, 1936. Phila., American Society for Testing Materials. 160 p., 9x6 in., paper, free on written request. The standards and tentative standards of the society which were in effect on January 1, 1936, are included in this index, with reference to the publication where they appear, and included also is a numerical list for locating any specification or method of test that has appeared.

CROSBY-FISKE-FORSTER HANDBOOK of FIRE PROTECTION. 8 ed. 1935. Ed. by R. S. Moulton; pub. and distrib. by National Fire Protection Association, Boston, and D. Van Nostrand Co., N. Y. 1154 p., illus., 7x5 in., lea., $4.50. A completely revised edition providing a comprehensive, authoritative review of accepted practice.

NATIONAL ELECTRICAL CODE HANDBOOK, based on the 1935 edition of the National Electrical Code. By A. L. Abbott. 3 ed. N. Y. and Lond., McGraw-Hill Book Co., 1936. 547 p., illus., 8x5 in., lea., $3.00. Discusses rules of the National Electrical Code where desirable for better understanding and explains the practical application of them.

Die PHOTOELEMENTE und IHRE ANWENDUNG. Pt. 1. Entwicklung und physikalische Eigenschaften. By B. Lange. Leipzig, J. A. Barth, 1936. 132 p., illus., 9x6 in., paper, 9.60 rm. The first portion of a comprehensive treatise upon photoelectric and photovoltaic cells and their uses in which the physical properties of photovoltaic, crystal, and electrolytic cells are set forth.

SOLUBILITY of NON-ELECTROLYTES. (American Chemical Society Monograph Series No. 17). By J. H. Hildebrand. 2 ed. N. Y., Reinhold Pub. Corp., 1936. 203 p., illus., 9x6 in., cloth, $4.50. Outlines a consistent theory of nonionic solutions helpful in practical problems, and brings up to date the study of the problems of solubility.

A STUDY by MEANS of PHOTOGRAPHY of the INTERRUPTION of MEDIUM POWER ELECTRICAL CIRCUITS. By J. Anderson, Chief Engineer of George Ellison, Ltd.; printed and published by Allday Limited, 128–130 Edmund St., Birmingham 3, England, 1935. 139 p., illus., 17x11 in., cloth, 5 guineas. Describes some of many thousand tests made by the author on medium power circuits, and reproduces over 3,000 photographs for a-c and d-c arcs between 20 and 11,000 amperes at about 440 volts, with information about arc formations in air, oil, and water.

STANDARD PRACTICES, published by Diesel Engine Manufacturers' Association, printed and distributed by Diesel Publications, 192 Lexington Ave., N. Y., 1935. 162 p., illus., 9x6 in., cloth, $2.00. Contains the standard practices and definitions adopted by the association, consideration being given also to electrical equipment.

# Industrial Notes

**Power Consumption at Ford Plant.**—Electric power used by the Ford Motor Co. in the Detroit area during 1935 amounted to 658,247,947 kilowatthours, exceeding the 1934 output by more than 145,000,000 kilowatthours. Practically all of the company's total usage of electricity in the Detroit area was generated and consumed in the Rouge plant. An important part of the company's present program of expansion and modernization is proceeding rapidly in No. 1 power house. The new installation includes a 1400-pound pressure boiler, a 110,000-kw turbogenerator, and a 15,000-kw turbogenerator. When the installation is completed, this will be the largest high-pressure steam plant in the world. Its capacity will be increased from about 270,000 horsepower to about 435,000 horsepower.

**Westinghouse Annual Report.**—Orders for 1935, according to the annual report of the Westinghouse Electric & Mfg. Co., totaled $123,629,333, compared with $106,473,226 in 1934, an increase of 16 per cent. Sales billed amounted to $122,588,555 as against $92,158,893 in 1934, an increase of 33 per cent. The net earned income was $11,983,380, compared with $189,562 in 1934, and is the highest reported in any year since 1929. The volume of the company's foreign business in 1935, obtained through the Westinghouse Electric International Co., showed a substantial increase over 1934.

**Cutler-Hammer, Inc., Appointment.**—R. J. Eckstein has been appointed manager of the Cleveland office of Cutler-Hammer, Inc., of Milwaukee, manufacturers of electric control apparatus. Mr. Eckstein joined the company 25 years ago.

**General Electric Annual Report.**—The 44th annual report of the General Electric Co. for the year 1935 shows orders received of $217,361,587 during last year, compared with $183,660,303 for 1934, an increase of 18 per cent. Sales billed amounted to $208,733,433, compared with the previous year's $164,797,317, an increase of 27 per cent. Net profit was $27,843,772, compared with $19,726,044 for 1934.

**Largest Gas-Cooled Generator for New York Edison.**—The largest and among the first hydrogen-cooled generators to be built has been ordered by the New York Edison Co. as part of a new 50,000-kw, 85 per cent power factor, 13,800-volt, 3600-rpm Westinghouse super-position turbine generator unit. The turbine will be a two-cylinder non-condensing impulse reaction unit consisting of a high pressure element developing 46,710 kw., at 1200 pounds—900°—200 pounds gauge back pressure.

**Building Gains in 1936.**—The construction industry continues to record large gains over the comparative levels of 1935. For February a contract total of $142,050,200, covering all branches of construction, was reported by F. W. Dodge Corp. for the 37 states east of the Rocky Mountains. This was practically 90 per cent larger than the total of only $75,047,100 reported for February 1935. Partly because of the unusually low temperatures and heavy snows the February contract volume was about 30 per cent lower than the total of $204,792,800 registered for January of this year. Total construction for the first two months of 1936 amounted to $346,843,000 as against only $174,821,000 for the corresponding two months of 1935, a gain over last year of 98 per cent. For residential building alone the contract volume for the first two months of 1936 totaled $68,615,000 or a gain of 76 per cent over the total of $39,027,000 for the corresponding two months of 1935.

**NEMA Standards.**—The National Electrical Manufacturers Association has released Publication 36-31, entitled "NEMA Rubber Insulated Building Wire and Cable Standards, National Electrical Code Grade Compound." This is to be followed shortly by publications covering 30 per cent grade compound and performance grade compound. This pamphlet contains the NEMA standards for the complete wire or cable which includes the conductor, insulation, fibrous covering, and lead sheath. Such items as physical properties and methods of test, insulation thicknesses, insulation test voltages, saturation of braid, etc., can be readily determined by referring to the standards in this publication. Copies of this 16-page pamphlet may be obtained from the National Electrical Manufacturers Association, 155 East 44th St., New York, at 25 cents per copy.

Publication 36-34 entitled "NEMA Magnet Wire Standards" is also now available. This publication contains the NEMA standards that have been developed for cotton covered, silk covered, and enameled round copper magnet wire. Such items as maximum permissible thickness of cotton or silk, method of making joints, etc., can readily be determined by referring to these standards. Copies are 25 cents each.

# Trade Literature

**Time Switches.**—Bulletin GEA-1427E, 8 pp. Describes types T-17 and T-27 general-purpose automatic time switches. General Electric Co., Schenectady, N. Y.

**Capacitors.**—Catalog 127, 24 pp. Describes capacitors for use in transmitting and industrial fields. Cornell-Dubilier Corp., 4377 Bronx Boulevard, New York.

**Connectors.**—Bulletin 3361, 4 pp. Describes drop-on, split bolt, house service and unit type solderless connectors. New price list is included. Line Material Co., South Milwaukee, Wis.

**Radio-Telephone Transmitting Equipment.**—Bulletin 309B, 12 pp. Describes radio telephone transmitting equipment for use by police departments. Western Electric Co., 195 Broadway, New York.

**Cable Grips.**—Bulletin, 4 pp. Describes various types of grips for pulling insulated wires and cables—aerial, underground, submarine, etc. Kellems Products, Inc., 100 Lafayette St., New York.

**Artificial Rubber.**—Booklet, 40 pp., "A Rubber Plantation in New Jersey." An interesting account of the development of "Thiokol," a synthetic rubber. Applications in the electrical field, particularly for cable protection, are shown. Thiokol Corp., Yardville, N. J.

**Lightning Arresters.**—Bulletin 385, 4 pp. Describes the new glass body types of Crystal Valve lightning arresters for distribution service in all voltage ranges from 1,000 to 15,000. Electric Service Supplies Co., Philadelphia, Pa.

**State Regulations for Trucks—Trailers.**—Booklet, 54 pp., 1936 edition "Truck and Trailer Size and Weight Restrictions." An authoritative interpretation of the rules and regulations of each state giving the permissible sizes and weights of trucks and trailers. Four Wheel Drive Auto Co., Clintonville, Wis.

**Pole Top Switches.**—Bulletin, 24 pp. Describes "PM-22" and "PM-23" group operated pole top disconnecting switches in ranges from 7.5 to 161 kv. Complete engineering data, dimensions, weights, manual and motor operating mechanisms, steel mounting frames and insulator data are included. Delta-Star Electric Co., 2400 Block, Fulton St., Chicago, Ill.

**Mercury Arc Rectifiers.**—Bulletin 1174, 8 pp. Describes mercury arc rectifiers for trolley bus service. Deals with the application of this type of converting equipment to the field of transportation. The suitability of rectifiers for power supply to trolley bus systems is demonstrated by interesting operating and performance data. Allis-Chalmers Mfg. Co., Milwaukee, Wis.

**Electric Industrial Trucks.**—Bulletin, 24 pp., "The Efficient, Economical Method of Handling Material." Describes electric industrial trucks and tractors equipped with Exide ironclad batteries. Illustrates the use of this equipment in various industries and includes battery construction and performance characteristics. The Electric Storage Battery Co., Philadelphia, Pa.

**Variable Speed Texrope Drives.**—Bulletin 1261, 12 pp. Describes new Vari-Pitch Texrope sheaves. Illustrates stationary controlled type and motion controlled type, together with the new Straitline automatic ball bearing motor base permitting complete adjustment while in operation. General dimension tables are included for both types covering a large number of sizes in from 2 to 8 grooves. Allis-Chalmers Mfg. Co., Milwaukee, Wis.

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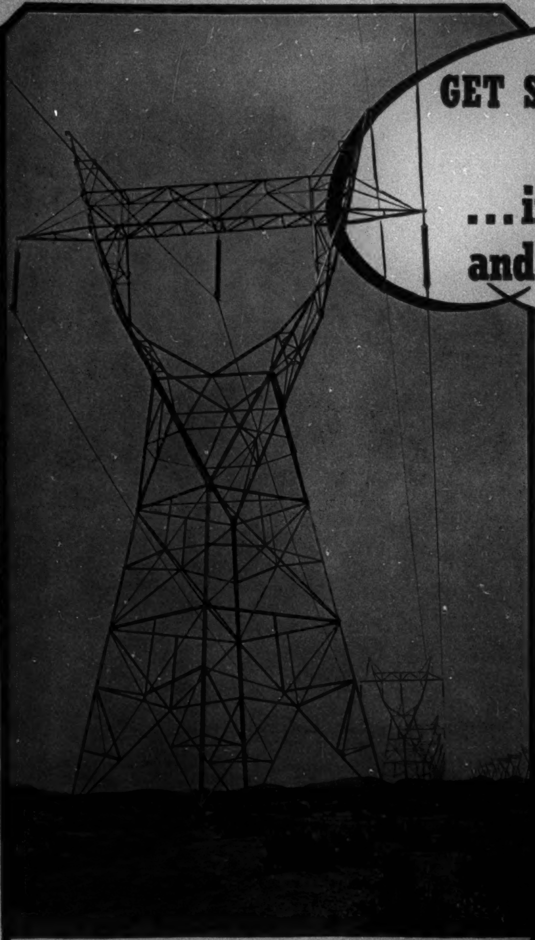
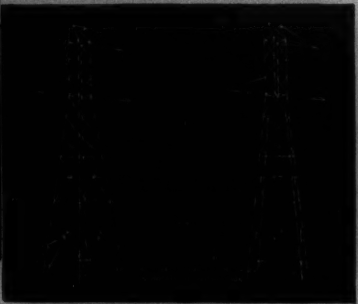


These 287,000 volt rotated towers are used by the Bureau of Power and Light, City of Los Angeles for their Boulder Canyon—Los Angeles lines across the Mojave Desert, a twin line about 250 miles long.

THE most severe loading of a tower due to a broken conductor together with a maximum transverse wind, is usually borne by two legs resulting in a pull at about a 45 degree diagonal.

Distribute this most severe loading evenly to all 4 legs by rotating the lower portion of the tower to this 45 degree angle, leaving the upper part in the regular position, and your savings in the cost of excavations and of anchor steel are considerable—as high as 30%.

This new development is the result of American Bridge experience in designing, fabricating and erecting thousands of towers for all kinds of uses. Call American Bridge Company technicians to assist in the study of your requirements.



Common type tower at left; American Bridge Rotated Type tower at right. On load plans transmission lines run vertically, maximum transverse wind horizontally, thus on common type tower 2 diagonally opposite legs carry resultant load. On American Bridge Rotated Type tower is seen distribution of resultant load to 4 legs, reducing greatly the maximum load on any 1 leg.

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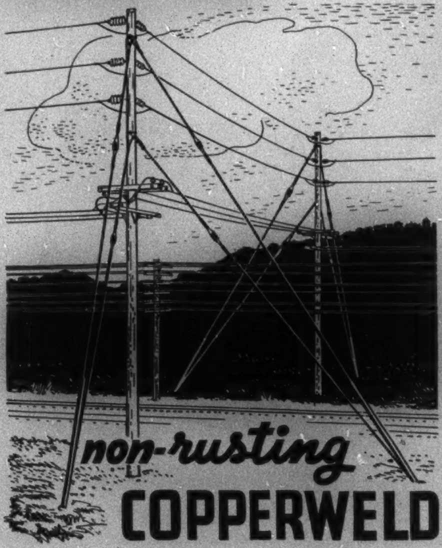
MEASURING MOTOR LOADS

# Guy Wires THAT LAST AS LONG AS THE LINE



You can save money on line maintenance by eliminating guy wire replacements. Many companies have proved that this is possible through standardizing on high strength, non-rusting Copperweld Guy Strand.

Check the renewals of guys on your property, and learn the amount of labor, material and truck time involved per guy. Then figure what would have been saved had these replacements been avoided.

Copperweld engineers will gladly assist you in this study.

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# Pole Stubbing Clamps for Economy

The set-up illustrated, using M. I. F. Wedged Band Type PA63-8 Stubbing Clamp set, was tested by attempting to tear pole away from stub. The test developed approx. 92,000 ft. lbs. overturning moment to break stub, cut from lower end of full-treated pine pole stubbed, at ground-line where diam. was 12″—stub being firmly keyed.

Hardware showed no appreciable distortion when removed in presence of group of Operating Engineers and Supts. viewing the tests. Ample strength assured for normal service requirements.

All castings for each Stubbing Clamp set are wired together for shipping. Pole Bands (4) and Stub Bands (4) of proper length are bundled flat. Bands vary 6″ in length for each 2″ in diam. of pole or stub.

Lighter type PA63-4, uses same castings and 4 heavier Bands, ends of which are lagged. Use should be limited to normal vertical loading or stresses along line tending to swing pole around on stub—while heavier type may be used universally at slightly higher cost.

Sample set of either type will be sent for actual field installation by Supt. or Engineer faced with pole salvage. State effective ground-line diam. of pole and stub.

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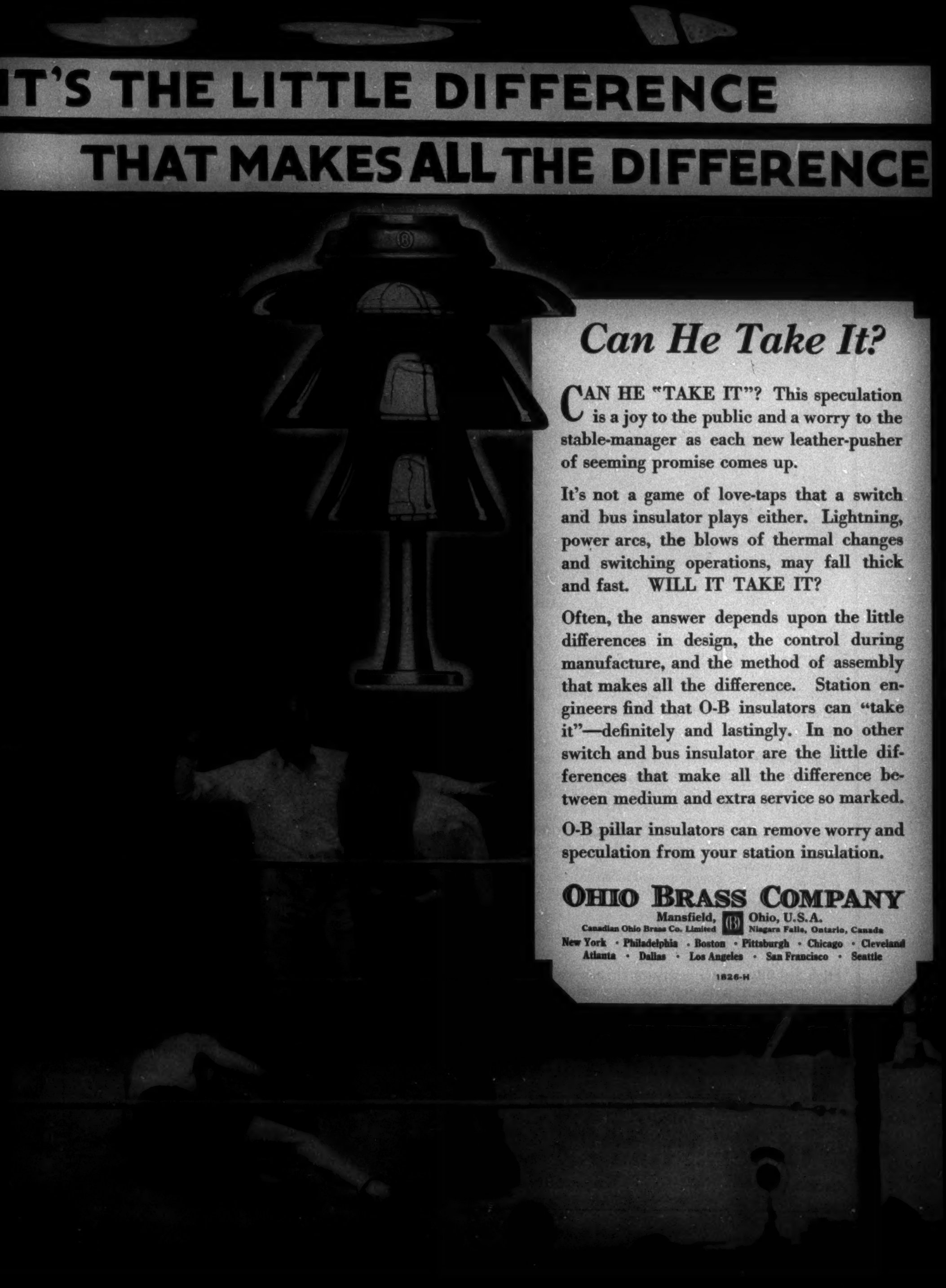

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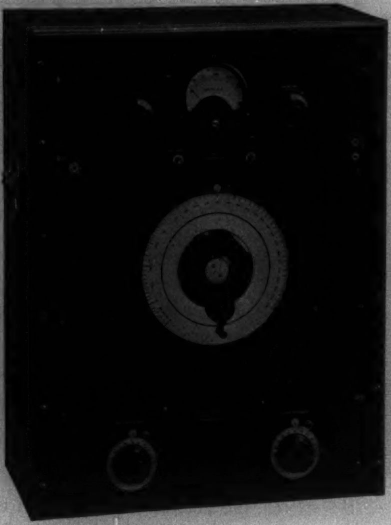
1826-H

# High Power Laboratory Oscillator



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**High Output:** **2 watts**—adequate for all laboratory needs without additional amplification—output voltage 130 on open circuit—output voltage read on linear-scale vacuum-tube voltmeter

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**Single Control:** calibration direct reading for every cycle throughout range

**High Stability:** new oscillator circuits—buffer stage—balanced push-pull detector—balanced power amplifier—frequency drift negligible—15 volt change in power line changes output by less than 1 cycle

**Type 713-A Beat-Frequency Oscillator . . . . $485.00**

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**· INSULATION ·**

---

# Universal Porcelain

- Best ingredients, thoroughly mixed, ground and shaped by steel dies and molds into insulators of intricate forms. Dimensions are held to extremely close limits. Pieces are carefully designed so as to be easily dischargeable from the mold, assuring a sound piece free of internal stresses.

Molds are carefully filled so that the material flows uniformly. Uniform pressures are applied while molding, reducing the possibility of cracking while drying and firing.

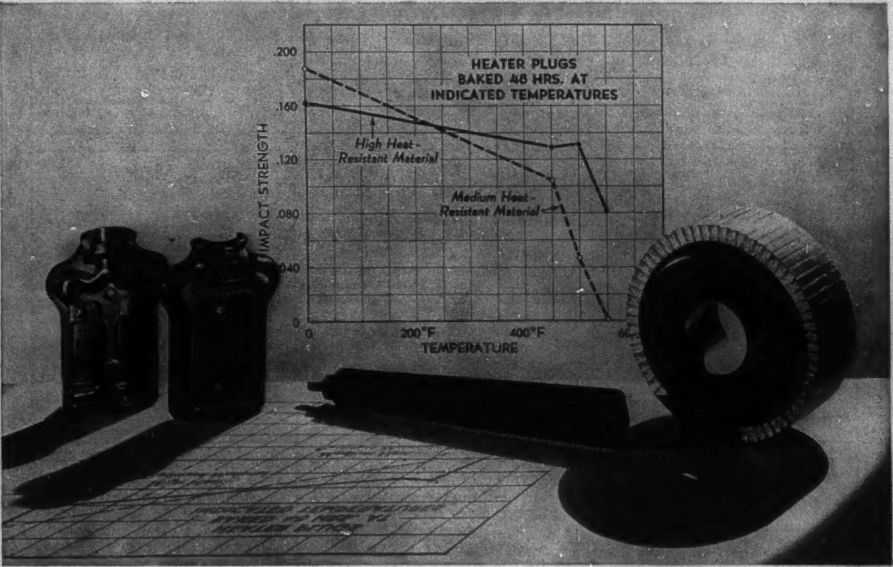
Designing and consulting service is free to customers.

**UNIVERSAL CLAY PRODUCTS CO**

*Sandusky Ohio*

CHICAGO OFFICE: [illegible]

# When Higher Heat-Resistance is Required...



**O**CCASIONALLY, engineers are confronted with the problem of designing or specifying Bakelite Molded parts which will be subjected to a higher degree of heat than molded parts are ordinarily called upon to sustain. Heater plugs and connectors, molded commutators and heating utensil handles are typical examples.

To meet these special requirements there are several types of mineral filled Bakelite Molded which possess this often desirable property of heat resistance to a far greater degree than the more commonly used forms. In addition these materials have better water resistance which makes them particularly suitable for outdoor service. The standard colors are black and brown.

These heat-resistant types of materials also possess the advantageous characteristics of the more commonly used forms of Bakelite Molded, including strength, electrical insulation value, and resistance to oils, acids, fumes, and most chemicals.

Our engineers would welcome an opportunity to cooperate with you in determining suitable applications of heat-resistant Bakelite Molded. We would also be glad to mail, upon request, a copy of our 48-page illustrated booklet 33M, "Bakelite Molded" which also gives A.S.T.M. tests of this and other types of molding materials.

—

*The above chart shows the impact strength tests of small heater plug parts made of heat-resistant Bakelite Molded, when these were exposed to relatively high temperatures. The several parts illustrated are typical examples of appropriate uses for these Bakelite heat-resistant materials.*

BAKELITE CORPORATION, 247 PARK AVENUE, NEW YORK, N. Y.
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To appear in the following issue, cards must be received not later than the 20th day of the month.

# Employment Bulletin

## Engineering Societies Employment Service

MAINTAINED for their members by the national societies of civil, mining, mechanical, and electrical engineers, in co-operation with other organizations. An inquiry to any of the three offices will bring full information.

A weekly bulletin of engineering positions open is available to members of the co-operating societies at a subscription of $3 per quarter or $10 per annum, payable in advance.

**In the interest of effective service, it is essential that members using the employment service keep the bureau office serving them advised at reasonable intervals concerning their availability for employment, concerning any change in status, and immediately upon acceptance of any employment.**

Employers interested in the following announcements should address replies to the key numbers indicated, and mail to the New York Office.

●

### Men Available

E.E., Carnegie Tech, age 34, single. Practical engr in constr, instal and servicing of furnaces, motors, generators, locomotives, pwr house eqpt and their control. Can handle men. C-3476-5179-Chicago.

I.E.E., '32, Pratt Inst, 25; 4 yrs exper elec maintenance and constr; 9 mo course in practical Diesel. Desires engg pos with advancement. Any location. Available on short notice. D-4670.

E.E. GRAD, 40; 17 yrs exper, constr, instal, maintenance, inspec, tests, repairs, pwr plants, substations, with yr each oprtg, distr high and low tension, etc. Knows So. Am. Linguist. C-2021.

ERECTING ENGR, 51; 20 yrs exper constr, maintenance, elec generating stations, swbds, complete substation erection, chem and indus plant instal, crushing and grinding machy, high pressure piping. C-8792.

E.E., B.S., 1935, Tau Beta Pi, single, 23. Elec products draftsman desires exper in elec pwr engg or des. Salary secondary if advancement is possible. Location immaterial. D-4483.

E.E., B.S., Clarkson Col Tech, Jan 1936, age 24. Extremely desirous of entering des, instal, maintenance work. Prefers to start at bottom and advance on merits. Domestic or foreign service. D-4641.

E.E., B.S., 1935, recent grad desires to make good in elec industry. Excellent math; young, single, Am. Salary secondary. D-4708.

E.E., B.S., Worcester Poly Inst, 1935, single, 24; 6 mos exper surveying and pwr station des, also draftg. Salary secondary if advancement is possible. D-4761.

E.E., S.B., MIT, 1934, single, 21. Was grad first quarter of class. Location, salary secondary to opportunity engg field. Specialized pwr generation, distr at Tech; also familiar with electronics. D-4782.

E.E., PENN STATE, 1936, desires a pos affording advancement in elec field, preferably with pwr co. Any location. Member of Tau Beta Pi, Pi Mu Epsilon. Available June 1936. D-4788.

E.E., 24, single; Sc.B., Sigma Xi, advanced course Lowell Inst, '35; 7 mos test, maintenance, constr burglar alarms; 6 mos special test, devpmt flowmeters. Desires permanent pos. Available immed. D-3458.

E.E., B.S., 1935, Sch of Tech, CCNY, single, 23; 4 yrs electrician, 2 yrs automobile ignition and repairs, expert typist. Salary and location secondary if advancement is possible. Available immed. D-4660.

A.B., B.S., E.E., Columbia, single, 28; 3 yrs supervision elevator maintenance and repairs. Present, prod and devpmt engr automotive ignition plant. Excellent ref. Desires hard work, real opportunity. Location immaterial. D-893.

MAINTENANCE ENGR, 35, with 15 yrs exper with pub util, Test Bureau, etc. Has knowledge of pwr plant elec instruments and systems apparatus. Location, N.Y.C. D-4736.

E.E., 45, desires connection in pwr plant oprn or management as asst to engr or exec; 15 yrs exper on pwr plant eng des, constr, oprn, test and maintenance. B-8379.

E.E., G.E. test course, 32, married, 8 yrs pub util exper as oprtg supt, holding co purchasing engr, analyst subsidiary oprns. Desires pos oprtg supt. Employed but seeking broader opportunity. B-9871.

E.E., 1926; D.Eng, 1929; Sigma Xi, licensed prof engr; married; 4 yrs exper in indus research, 3 yrs teaching E.E., math. physics. Desires teaching or research work. Available July 1. D-1842.

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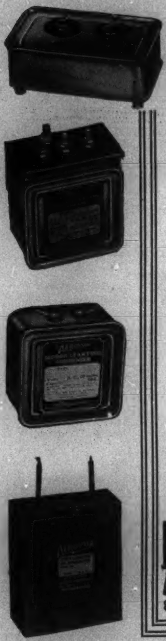

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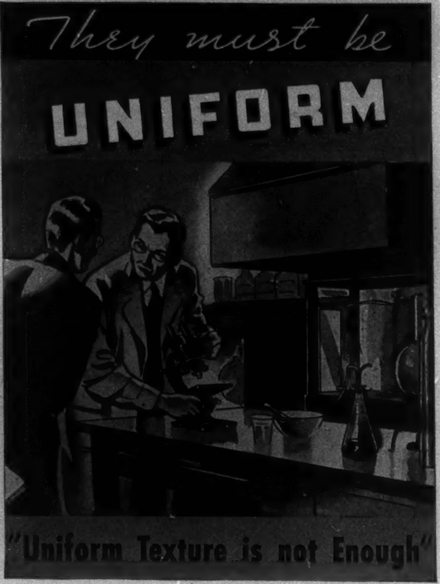
WANTED FOR THE PANAMA CANAL. Electrical Designers, entrance salaries $208.33 and $270.83 a month. Temporary employment for about six months. Must be electrical engineering graduates from a college or university of recognized standing and have considerable experience in electrical engineering in connection with electrical installations in various types of buildings. Must be American citizens (final papers) not over 45 years, in good health. Free steamship transportation from New York or New Orleans, salary beginning on date of sailing and free return steamship transportation upon satisfactory termination of service but no transit time. For further particulars write "Chief of Office, The Panama Canal, Washington, D. C."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"Uniform Texture is not Enough"

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**An "SA" Series grade is not "just another brush." It is an engineering achievement.**

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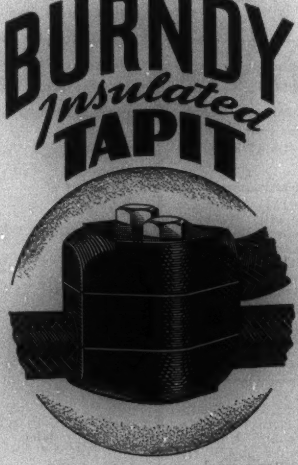

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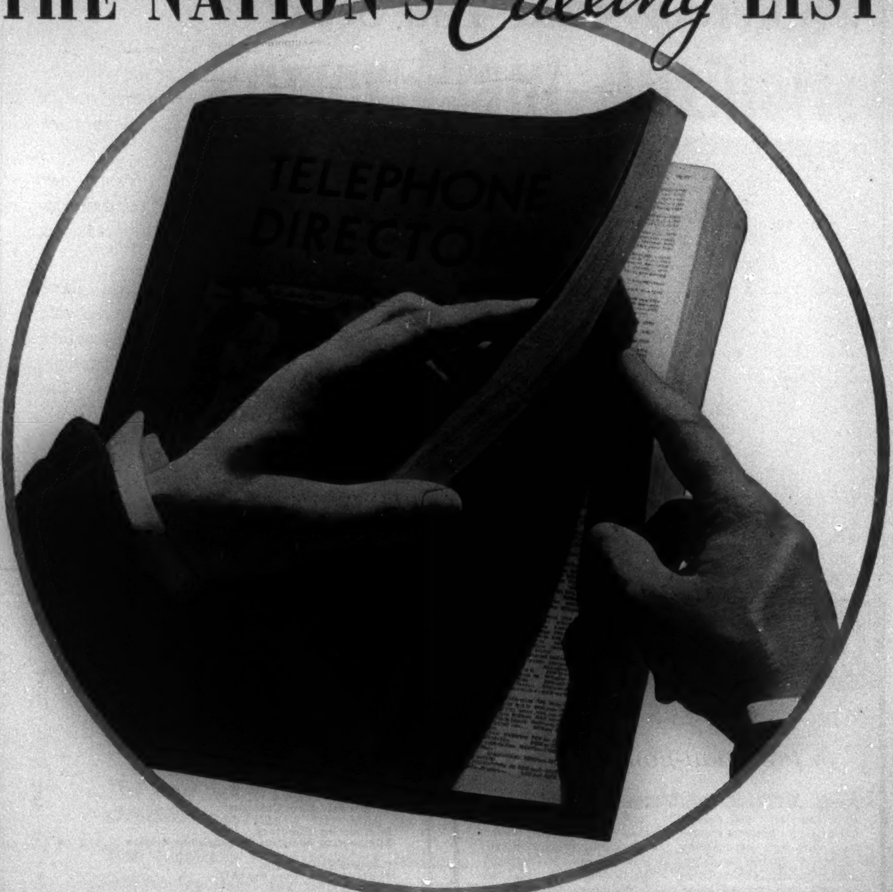

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—direct factory financing on a new 5% plan.
—floor plan for display stokers.
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—participation in local advertising.
—national advertising on stokers; the company's products advertised in more than 100 trade papers.
—traveling representatives to help the dealer train men, survey jobs and close sales.

Write for literature and dealer plan; we will advise you if your territory is still unassigned.

**LINK-BELT COMPANY**
Stoker Division 2410 W. 18th St.,
ex Chicago

Send dealer plan to:

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Address..........................................

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# *New* Circuit Breakers *for* Power Plant Auxiliaries

**The new I-T-E Type K circuit breaker was designed by central station engineers expressly for use in power plant service.**

**The features incorporated include those features lacking in the devices ordinarily used for protection and control of auxiliaries. The RESULT is a circuit breaker combining contactor and motor starter characteristics.**

**Small and compact—solenoid operated—latched in—high interrupting capacity—adjustable overload—alloy butt contacts—low maintenance—long life—safe operation.**

**The design of Type K circuit breaker is such that standard remote control wiring, 2 or 3 wire, and either momentary contact or maintained contact control, is possible.**

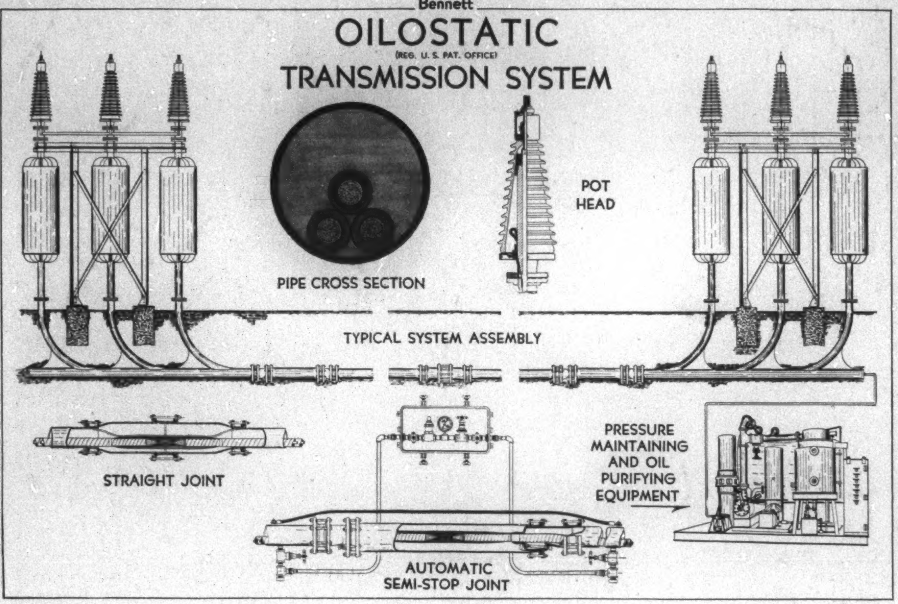
**Complete information on request.**

*Offices in Principal Cities*

**I-T-E CIRCUIT BREAKER CO., PHILADELPHIA, PA.**

Bennett

# OILOSTATIC
(REG. U. S. PAT. OFFICE)
# TRANSMISSION SYSTEM


PIPE CROSS SECTION
POT HEAD
TYPICAL SYSTEM ASSEMBLY
STRAIGHT JOINT
PRESSURE MAINTAINING AND OIL PURIFYING EQUIPMENT
AUTOMATIC SEMI-STOP JOINT

IN the Oilostatic Transmission System developed and manufactured by the Okonite-Callender Cable Co., Inc., the insulated conductors are in buried metal pipe filled with oil, maintained under a constant pressure. Above typical Oilostatic layout shows simplicity of pumping, valve, joint and pothead equipment.

- *with Oilostatic:*

NO DUCTS, NO LEAD SHEATH. NO VOIDS IN THE INSULATION. HIGHER DIELECTRIC STRENGTH. GREATER INSULATION STABILITY. INCREASED CURRENT CARRYING CAPACITY. CABLE OPERATION AT VOLTAGES HIGHER THAN 132,000 VOLTS.

Right-of-way and other physical problems going with overhead transmission can be solved by Oilostatic at great savings in installation and maintenance costs.

All of these advantages, and more, are made available by Oilostatic Transmission System.

Two Oilostatic installations, one at 132 kv. and one at 66 kv. are already in successful operation.

Our Engineering services are always available. Inquiries on specific projects are invited.

**THE OKONITE COMPANY**
Founded 1878
and
HAZARD INSULATED WIRE WORKS DIVISION
THE OKONITE-CALLENDER CABLE COMPANY, INC.
EXECUTIVE OFFICE: PASSAIC, N. J.

New York, Boston, Chicago, Detroit
Philadelphia, Pittsburgh, Washington, San Francisco
Los Angeles, Seattle, Dallas, Atlanta
Factories: Passaic, N. J. Wilkes-Barre, Pa. Paterson, N. J.

OKONITE QUALITY CANNOT BE WRITTEN INTO A SPECIFICATION